

## 5 Measuring Climate Sensitivity to CO<sub>2</sub> Forcing

### 5.1 Introduction

The magnitude of the sensitivity of Earth's climate to increasing concentrations of CO<sub>2</sub> is at the heart of the scientific debate on anthropogenic climate change, and also the public debate on the appropriate policy response to increasing CO<sub>2</sub> in the atmosphere. Equilibrium Climate Sensitivity (ECS) refers to the expected amount of warming averaged over the Earth's surface in response to a doubling of CO<sub>2</sub>, after all climate systems have had time to adjust. Some systems, like temperatures in the troposphere, adjust very rapidly. Others may take decades or even centuries, such as the deep ocean and the cryosphere. A related metric which is sometimes more helpful for analysis on shorter time scales is the Transient Climate Response (TCR) defined as the amount of warming after 70 years in which atmospheric CO<sub>2</sub> goes up by one percent annually.

In 1979 the Charney (1979) Report for the US National Academy of Sciences proposed that the most likely value for ECS was 3.0°C plus or minus 1.5°C. With only minor variations this range was adopted and reaffirmed by the IPCC until the most recent AR6. The ECS range between 1.5 and 4.5°C is characterized by the IPCC AR5 as the *likely* range (66 percent probability); the AR5 stated that ECS is *extremely unlikely* (95 percent probability) to be below 1.0°C and very unlikely (90 percent probability) to exceed 6.5°C. This range of ECS values has remained stubbornly wide, despite many individual studies claiming to narrow it. Most recently, the IPCC AR6 narrowed its assessment of the *likely* range of ECS to 2.5–4.0°C and the *very likely* range to be between 2.0 and 5.0°C. This narrowing of the range on the low end is disputed, as will be discussed below.

Uncertainties about ECS are highly consequential for policy making. As will be discussed in Chapter 13, economic models take the ECS value from climate science and use it to project the costs of CO<sub>2</sub> emissions. The traditional ECS value (3.0 °C) has typically yielded modest global social costs of CO<sub>2</sub> emissions, enough to justify some policy actions though mostly deferred to later in the century. If ECS is very high (4.5°C or above) aggressive immediate emission controls become more imperative, whereas values closer to 2.0°C have been shown to imply that no CO<sub>2</sub> emission controls are economically justifiable (Dayaratna et al. 2016, 2020). Obtaining a precise ECS estimate is therefore important for policy guidance. Obtaining a precise estimate is impossible, policy making needs to account for the uncertainty.

### 5.2 Model-based methods of computing climate sensitivity to GHGs

The ECS range has been obtained primarily by examining the behaviour of climate models, but since key components of models are under the control of modelers this is not dispositive of the actual climate's sensitivity. There are approximately three dozen computer climate models operated by research groups around the world (Cannon 2024). GCMs are valuable tools for understanding the climate system from a theoretical perspective. But the models have become so complex, often with 1 million or more lines of computer code (Brown-Steiner 2024), that it would be prohibitively expensive and time consuming for anyone to replicate the models' projections of climate change, let alone test the myriad model approximations embedded in the computer codes; a climate model typically takes hundreds of experts many years to develop (McSweeney and Hausfather 2018). As a result, these models are published in the scientific literature with little to no independent evaluation (Pirtle et al 2010). Climate modeling thus stands as an unusual class of scientific endeavor wherein researchers validating the scientific claims of others — a hallmark of science (National Academy of Science 2019)— becomes impractical, if not impossible.

In large-scale General Circulation Models (GCMs, aka climate models) ECS is not imposed as a direct parameter, instead it emerges from the behaviour of the underlying components of the model. Collections of parameterizations are often chosen to produce an expected value of climate sensitivity, particularly with regards to sub-grid-scale cloud processes. Otherwise plausible models and parameter selections have been discarded because of perceived conflict with this warming rate, or aversion to a model's climate sensitivity being outside an accepted range. For example, Mauritsen and Roeckner (2020) state the following regarding their Max Planck Institute climate model:

"We have documented how we tuned the MPI-ESM1.2 global climate model to match the instrumental record of warming; an endeavor which has clearly been successful. Due to the historical order of events, the choice was to do this practically by *targeting an ECS of about 3 K using cloud feedbacks*, [emphasis added] as opposed to tuning the aerosol forcing."

In other words, the modelers chose an ECS value of 3°C and then tuned the cloud parameterizations to match their intended result.

Direct warming from CO<sub>2</sub> doubling is only about 1°C (Hall and Manabe 1997); ~~the rest, to the extent more happens, arises due~~ higher values arise from climate feedbacks that are not explicitly resolved by the model but rely on parameterizations of physical processes ~~which are inherently more difficult to predict and model~~. Higher values of ECS arise primarily from positive cloud feedbacks. The magnitude, and even the sign, of cloud feedbacks is the greatest source of uncertainty. Elements of cloud feedback include changes in the latitudinal distribution of clouds, changes in the distribution of cloud height (changes in low versus high clouds), changes to the phase of clouds (ice versus liquid), changes in cloud particle size (associated with changes in concentration and/or composition of aerosol particles), changes in the precipitation efficiency of clouds, and even changes in how clouds are distributed over the daily solar cycle [source 35]. It is difficult for climate models to simulate any of these cloud processes correctly owing to their small scale, let alone predict how they will change in the future. Further, cloud processes modulate the magnitudes of the water vapor, lapse rate, and the surface albedo feedbacks [source 36].

ECS can be determined from climate model simulations by doubling the concentration of CO<sub>2</sub>, allowing several centuries for the warming to equilibrate. To avoid the necessity of long simulations, "effective climate sensitivity" is commonly evaluated from a 150-year simulation in response to a sudden quadrupling of CO<sub>2</sub>. The spread of ECS values from the CMIP5 climate models (used in the AR5) was 2.0–4.7°C; the spread has increased for the CMIP6 models (used in the AR6) to between 1.8 and 5.7°C [sources 37,38]. Far from the science being settled in relation to the response of the climate system to increasing greenhouse gas concentrations, insofar as it is represented by climate models, uncertainties appear to be growing. The main cause of the overall upward shift in ECS in CMIP6 relative to CMIP5 is a larger positive cloud feedback, driven by changes to the cloud parameterizations in many CMIP6 models.[source 39]

~~THIS ISN'T VERY RELEVANT.~~ While the models are often touted as being accurate representations of the "basic physics" governing the climate system, they still have problems with model "drift," in which the models slowly change temperature over centuries for no apparent reason (Grandey et al. 2023). The tendency to drift is adjusted for by climate modelers imposing the arbitrary assumption that Earth's climate system does not produce long-term climate change, unless caused by humans (Sen Gupta et al 2013). Suppressing all slow-moving warming and cooling in this way biases model-based research away from potential natural causes of climate change since it implies there can be no warming trends except in response to external forcing. In addition recent research suggests many



~~models do not even conserve energy (Irving 2021) — a violation of the First Law of Thermodynamics. The First Law holds that energy can be neither created nor destroyed; to the extent that climate models fail to conserve energy, it can spontaneously appear (or disappear) for no apparent reason, causing a fictitious temperature change. This is a particularly important consideration since global warming theory is first and foremost based upon tiny changes in the global energy balance assuming the First Law holds.~~

Because of concerns about model tuning and the high sensitivity to cloud parameterizations, the IPCC AR6 (2021) did not rely on climate model simulations in their assessment of climate sensitivity, relying on other methods in its assessment instead, chiefly a recent empirical estimate.

### 5.3 Data-driven methods of computing climate sensitivity to GHGs

Climate sensitivity can also be estimated from instrumental records of surface temperatures and ocean heat content, combined with estimates of how climate forcings (e.g., greenhouse gases, solar, volcanoes, aerosols) have changed in the past. **[source 40]** Using this information, a simple empirical model called an Energy Balance Model can be estimated. It requires estimating a feedback parameter ~~which appears in the denominator of the resulting equation for ECS. NO EQUATIONS~~, whose uncertainties are highly amplified in the resulting ECS (Roe and Baker, 2007). ~~A small amount of uncertainty about the number in the denominator of a fraction can lead to very large uncertainties in the magnitude of the fraction itself. Roe and Baker (2007) pointed out that for this reason uncertainties in climate feedbacks are “highly amplified” in the resulting ECS.~~

The accuracy of the data-driven methods depends on the quality of the input data. Assumptions are needed about ocean heat storage, and the ocean data is inadequate. The greatest source of uncertainty is the amount and composition of aerosol particles and their interactions with cloud radiative properties (the so-called aerosol indirect effect). Climate models exhibit warming in response to GHGs but cooling in response to aerosols (Schwartz et al. 2007). Observed 20<sup>th</sup> century warming can be shown to be consistent either with low ECS and low aerosol cooling or high ECS and high aerosol cooling. Since fossil fuel use adds both GHGs and aerosols to the atmosphere, both effects need to be estimated to isolate the warming effect of CO<sub>2</sub>. Over time, the IPCC’s estimate of the cooling effect of aerosols has declined (Lewis 2022).

Paleoclimate proxies are also used to evaluate the sensitivity of past climates, by comparing paleoclimate changes in the Earth’s temperatures to estimates of changes in forcings. The two most informative periods are the last glacial maximum (around 20,000 years ago), which was about 3–7°C colder than today, and a mid-Pliocene period (roughly three million years ago), which was 1–3°C warmer than today. **[source 41]** The limits on cooling during the last glacial maximum give the best single evidence that high values of climate sensitivity are unlikely. However, paleoclimate estimates are associated with very large uncertainties in the estimated temperatures and forcings. Further, estimates of climate sensitivity based on past climate states may not be representative of the current state of the climate system.

A recurring theme in the climate literature is that ECS estimates based on historical data turn out to be smaller than ECS estimates inferred from climate models (Sherwood and Forest 2024). ~~An early empirical estimate (Stern and Kaufmann 2000) was 1.6°C, though this predated development of the Energy Balance Model method. Figure 5.1 shows the point or best estimates from 17 subsequent studies all appearing in the peer-reviewed literature since 2012. The Charney range is shown for contrast. The average ECS point estimate in the post-2012 sample is 1.8°C. The highest estimate, from~~

Sherwood et al. (2020), is shown in red; it is the one that was highlighted by the IPCC AR6 and used to guide their assessment of the ECS range (Forster et al. 2021). The one adjacent to it, Lewis (2022), was published subsequent to the AR6 and presented an extensive critique of Sherwood et al. (2020).

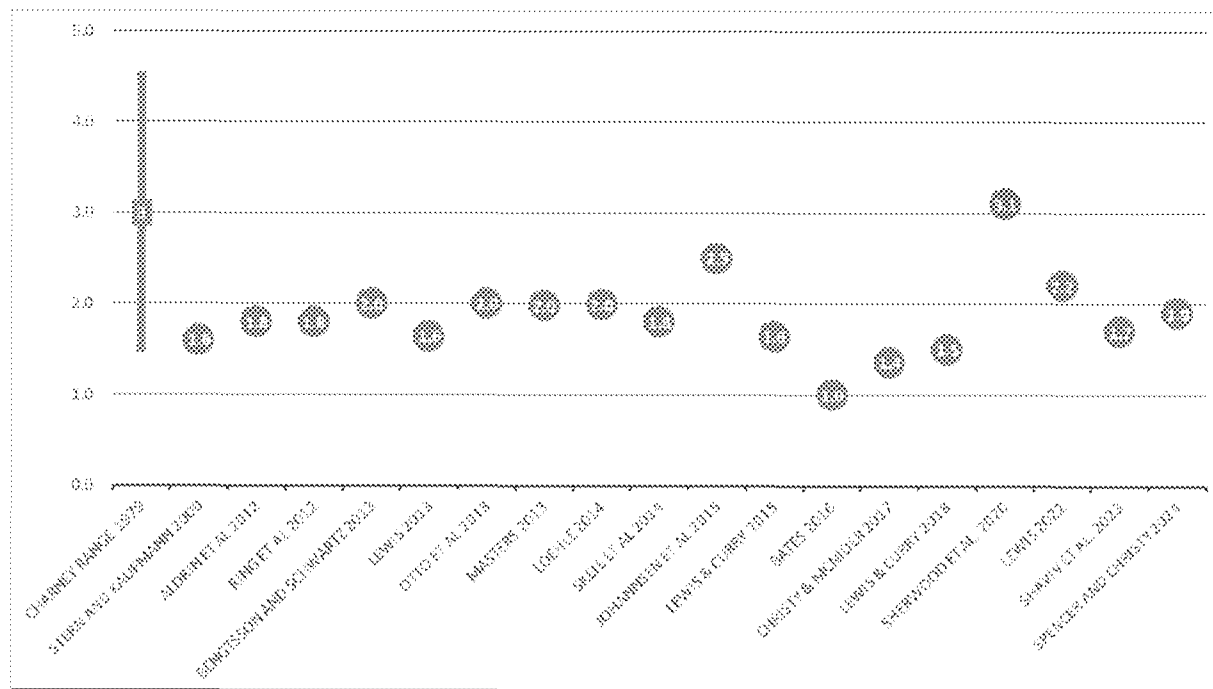


Figure 5.1: Empirical best estimates of ECS. Vertical axis: °C.

**[Judy I reinserted this Figure as I think it is an important visual indicator that Lewis 2022 is not a one-off outlier.]**

**I don't this this is needed. Lewis (2022) is not a historical empirical method, but rather uses the same approach as Sherwood et al. and AR6 in combining historical, paleo and feedback approaches. I don't think that the older ones are useful because the data is pretty old, and methods outdated. Lewis (2022) is clearly within the the AR5 range, I don't think we need to resurrect the old stuff.**

Key concerns raised by Lewis include methodological errors, outdated input values, and use of subjective versus objective Bayesian priors in the analysis. Lewis' analysis found that climate sensitivity is estimated to be much lower and better constrained than in the Sherwood et al. analysis – median 2.16°C (1.75–2.7°C in the 17–83 percent likely range), and 1.55–3.2°C in the 5–95 percent very likely range. Lewis' analysis implies that climate sensitivity is considerably more likely to be below 2°C than above 2.5°C. The IPCC AR6 estimated only a 5 percent probability that ECS was below 2.3°C, whereas Lewis (2022) estimated it to be over 50 percent. The most recent publications on the debate between Sherwood et al. and Lewis further defend their respective positions: Sherwood and Foster (2024) and Lewis (2025).

A recent argument, which the IPCC AR6 emphasized, is that data-driven ECS estimates might understate the future warming response to GHGs based on a so-called “pattern effect” (Forster et al 2021). The tropical Pacific is believed to be highly influential on the overall efficiency with which the

Earth's climate radiates heat to space, but in some regions heat is more efficiently removed from the climate system than from others. If in a warming climate there is a weakening of the west-to-east temperature gradient in the tropical Pacific the result would be a concentration of warming in a region where heat is less efficiently removed, raising the ECS of the Earth's climate system. Most climate models simulate that rising GHGs will weaken the east-west temperature gradient, which led the IPCC in the AR6 to conclude that data-driven ECS estimates understated the *future* ECS value.

However, Seager et al. (2019) pointed out that, contrary to models, the east-west temperature gradient has been strengthening rather than weakening over time. They further argued that the mechanism predicting otherwise in climate models was based on a faulty characterization of oceanic dynamics and there is no reason to expect the gradient to weaken. A similar argument was recently made by Lee et al. (2024), who concluded that “the trajectory of the observed trend reflects the response to increasing GHG loading in the atmosphere”; in other words GHG warming should lead to a future strengthening rather than a weakening of the temperature gradient. Increased efficiency of atmospheric cooling implies, if anything, that the future ECS in a warming climate may be *lower* than current estimates.

### 5.5 Transient Climate Response

The Transient Climate Response (TCR) is of greater utility in providing an observational constraint on climate sensitivity. TCR is the amount of warming that would occur at the time when CO<sub>2</sub> doubles, having increased gradually by 1 percent each year over a period of 70 years. Relative to the ECS, observationally-determined values of TCR avoid the problems of uncertainties in ocean heat uptake and the fuzzy boundary in defining equilibrium arising from a range of timescales for the longer-term feedback processes (e.g., ice sheets). TCR is more generally related to peak warming and better constrained by historical warming, than ECS. The IPCC AR6 judged the *very likely* range of TCR to be 1.2–2.4°C. **[source 47]** In contrast to ECS, the upper bound of the TCR is more tightly constrained. For comparison, the TCR values determined by Lewis (2023) is 1.25 to 2.0°C, showing much better agreement with the AR6 values than was seen in a comparison of the ECS values.

A related but more flexible parameter is the Transient Response to cumulative carbon Emissions, or TCRE, which relates global temperature change to the cumulative emissions. TCRE is based upon a linear relationship between global average temperature and cumulative emissions, which holds for cumulative emissions of up to 2 teratons of carbon. For a given value of TCRE, we can calculate the estimated amount of warming expected over a future period in response to scenarios of cumulative carbon emission. The IPCC AR6 provides a *very likely* range for TCRE of 1.0–2.3°C, with a median value of 1.6°C.<sup>48</sup>

As will be discussed in Chapter 6 a real-world ECS below the model average is supported by studies which show climate models on average estimate too much warming at the surface and in the troposphere compared to observations over the past 50 years. Also it aligns with evidence from consistent fingerprinting (Section 7) that model responses to GHGs need to be scaled down quite a bit to align with observed trends.

### 5.6 Summary

In the past 5 years, there is a growing realization that climate models are not fit for the purpose of determining the sensitivity of the climate to increasing CO<sub>2</sub> (ECS), owing to the dependence of this sensitivity on poorly resolved processes related to clouds and water vapor.

Data-driven approaches using historical data and paleoclimate reconstructions are now regarded as more reliable for determining ECS, but their reliability is diminished by data inadequacies. The IPCC AR6 upper bound for the *likely* range of ECS is 4.0°C, lower than the AR5 value of 4.5°C. This lowering of the upper bound seems well justified by the paleoclimatic estimates of the ECS. The IPCC AR6 lower bound for the *likely* range of ECS is 2.5°C, substantially higher than the AR5 value of 1.5°C. This raising of the lower bound of the likely range of ECS has received a substantial challenge from the analysis of Lewis (2022, 2025) that finds the lower bound of the likely range to be 1.75°C with a median value of 2.16°C. Other lines of evidence supporting a lower bound on the ECS range below the IPCC AR6 value are discussed in Chapters 6 and 7.

Estimates of the transient climate response (TCR; TCRE) are more tightly constrained on the upper bound than the ECS.

**[Judy I took out the assessed value statement since I don't think we need to generate one and I wouldn't know how to do it] AGREED**

Mauritsen, T., & Roeckner, E. (2020). Tuning the MPI-ESM1.2 global climate model to improve the match with instrumental record warming by lowering its climate sensitivity. *Journal of Advances in Modeling Earth Systems* 12, e2019MS002037; <https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2019MS002037>

Zelinka, M. D., Myers, T. A., McCoy, D. T., Po-Chedley, S., Caldwell, P. M., Ceppi, P., et al. (2020). Causes of higher climate sensitivity in CMIP6 models. *Geophysical Research Letters*, 47, e2019GL085782. <https://doi.org/10.1029/2019GL085782>

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**From:** Ross McKittrick <ross.mckitrick@gmail.com>  
**Sent:** Thursday, May 1, 2025 2:14 PM  
**To:** Judith Curry; Steven Koonin; John Christy; Roy W. Spencer; Travis Fisher  
**Subject:** Ch 5 ECS  
**Attachments:** 5 Climate Sensitivity.May1.Merged.docx

Hi Judy

I posted (& attached) a version of your ECS chapter that cleans up the formatting and merges back in some of the text I had included previously that I think helps it connect to the IAM discussion. I added a couple of comments in red font. I'm reluctant to include a group statement at the end about a likely ECS range. Also I converted the superscripts to insertions where the (name, date) citation will need to be inserted.

Ross

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spontaneously appear (or disappear) for no apparent reason, causing a fictitious temperature change. This is a particularly important consideration since global warming theory is first and foremost based upon tiny changes in the global energy balance assuming the First Law holds.

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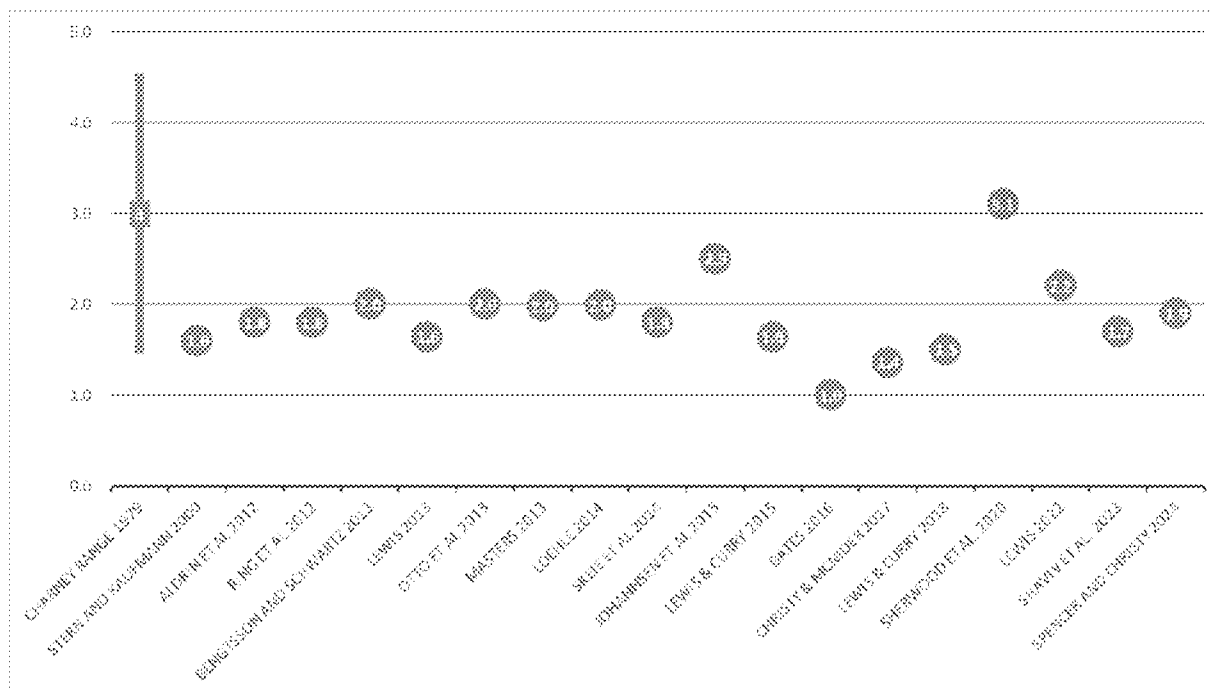


Figure 5.1: Empirical best estimates of ECS. Vertical axis: °C.

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Key concerns raised by Lewis include methodological errors, outdated input values, and use of subjective versus objective Bayesian priors in the analysis. Lewis' analysis found that climate sensitivity is estimated to be much lower and better constrained than in the Sherwood et al. analysis – median 2.16°C (1.75–2.7°C in the 17–83 percent likely range), and 1.55–3.2°C in the 5–95 percent very likely range. Lewis' analysis implies that climate sensitivity is considerably more likely to be below 2°C than above 2.5°C. The IPCC AR6 estimated only a 5 percent probability that ECS was below 2.3°C, whereas Lewis (2022) estimated it to be over 50 percent. The most recent publications on the debate between Sherwood et al. and Lewis further defend their respective positions: Sherwood and Foster (2024) and Lewis (2025).

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### 5.5 Transient Climate Response

The Transient Climate Response (TCR) is of greater utility in providing an observational constraint on climate sensitivity. TCR is the amount of warming that would occur at the time when CO<sub>2</sub> doubles, having increased gradually by 1 percent each year over a period of 70 years. Relative to the ECS, observationally-determined values of TCR avoid the problems of uncertainties in ocean heat uptake and the fuzzy boundary in defining equilibrium arising from a range of timescales for the longer-term feedback processes (e.g., ice sheets). TCR is more generally related to peak warming and better constrained by historical warming, than ECS. The IPCC AR6 judged the *very likely* range of TCR to be 1.2–2.4°C. **[source 47]** In contrast to ECS, the upper bound of the TCR is more tightly constrained. For comparison, the TCR values determined by Lewis (2023) is 1.25 to 2.0°C, showing much better agreement with the AR6 values than was seen in a comparison of the ECS values.

A related but more flexible parameter is the Transient Response to cumulative carbon Emissions, or TCRE, which relates global temperature change to the cumulative emissions. TCRE is based upon a linear relationship between global average temperature and cumulative emissions, which holds for cumulative emissions of up to 2 teratons of carbon. For a given value of TCRE, we can calculate the estimated amount of warming expected over a future period in response to scenarios of cumulative carbon emission. The IPCC AR6 provides a *very likely* range for TCRE of 1.0–2.3°C, with a median value of 1.6°C.<sup>48</sup>

As will be discussed in Chapter 6 a real-world ECS below the model average is supported by studies which show climate models on average estimate too much warming at the surface and in the troposphere compared to observations over the past 50 years. Also it aligns with evidence from consistent fingerprinting (Section 7) that model responses to GHGs need to be scaled down quite a bit to align with observed trends.

### 5.6 Summary

In the past 5 years, there is a growing realization that climate models are not fit for the purpose of determining the sensitivity of the climate to increasing CO<sub>2</sub> (ECS), owing to the dependence of this sensitivity on poorly resolved processes related to clouds and water vapor.

Data-driven approaches using historical data and paleoclimate reconstructions are now regarded as more reliable for determining ECS, but their reliability is diminished by data inadequacies. The IPCC AR6 upper bound for the *likely* range of ECS is 4.0°C, lower than the AR5 value of 4.5°C. This lowering of the upper bound seems well justified by the paleoclimatic estimates of the ECS. The IPCC AR6 lower bound for the *likely* range of ECS is 2.5°C, substantially higher than the AR5 value of 1.5°C. This raising of the lower bound of the likely range of ECS has received a substantial challenge from the analysis of Lewis (2022, 2025) that finds the lower bound of the likely range to be 1.75°C with a median value of 2.16°C. Other lines of evidence supporting a lower bound on the ECS range below the IPCC AR6 value are discussed in Chapters 6 and 7.

Estimates of the transient climate response (TCR; TCRE) are more tightly constrained on the upper bound than the ECS.

**[Judy I took out the assessed value statement since I don't think we need to generate one and I wouldn't know how to do it]**

Mauritsen, T., & Roeckner, E. (2020). Tuning the MPI-ESM1.2 global climate model to improve the match with instrumental record warming by lowering its climate sensitivity. *Journal of Advances in Modeling Earth Systems* 12, e2019MS002037; <https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2019MS002037>

Zelinka, M. D., Myers, T. A., McCoy, D. T., Po-Chedley, S., Caldwell, P. M., Ceppi, P., et al. (2020). Causes of higher climate sensitivity in CMIP6 models. *Geophysical Research Letters*, 47, e2019GL085782. <https://doi.org/10.1029/2019GL085782>

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**From:** Steven Koonin <steven.koonin@gmail.com>  
**Sent:** Tuesday, May 6, 2025 2:47 PM  
**To:** 'Ross McKittrick'; 'Judith Curry'  
**Cc:** 'John Christy'; 'Roy W. Spencer'; 'Travis Fisher'  
**Subject:** RE: edits to Chapter 12  
**Attachments:** ~WRD3425.jpg

I'm OK with the energy cost material.

SEK

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**From:** Ross McKittrick <ross.mckittrick@gmail.com>  
**Sent:** Tuesday, May 6, 2025 1:57 PM  
**To:** Judith Curry <curry.judith@gmail.com>  
**Cc:** Steven Koonin <steven.koonin@gmail.com>; John Christy <climateman60@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>  
**Subject:** Re: edits to Chapter 12

I added a couple of paragraphs on the connection to energy costs. Let me know if they are ok.

On Tue, May 6, 2025 at 12:26 PM Judith Curry <curry.judith@gmail.com> wrote:

Thx, I'm good with these changes. The AR6 statement is really weasel-y

On Tue, May 6, 2025 at 8:52 AM Steven Koonin <steven.koonin@gmail.com> wrote:

See attached.

Note at the end the criticism of the IPCC. It's certainly justified and, I think, appropriate. You might disagree on the latter point.

SEK

--



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CFAN - Climate Forecast Applications Network  
Reno, NV USA

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<http://www.cfanclimate.net>

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**From:** Judith Curry <curry.judith@gmail.com>  
**Sent:** Tuesday, May 6, 2025 2:22 PM  
**To:** Ross McKittrick  
**Cc:** Steven Koonin; John Christy; Roy W. Spencer; Travis Fisher  
**Subject:** Re: edits to Chapter 12

all looks good, i'll put together a final version of Ch12

On Tue, May 6, 2025 at 10:57 AM Ross McKittrick <[ross.mckittrick@gmail.com](mailto:ross.mckittrick@gmail.com)> wrote:  
I added a couple of paragraphs on the connection to energy costs. Let me know if they are ok.

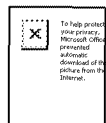
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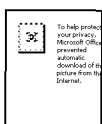
See attached.

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**From:** Ross McKittrick [ross.mckittrick@gmail.com]  
**Sent:** 5/6/2025 5:57:08 PM  
**To:** Judith Curry [curry.judith@gmail.com]  
**CC:** Steven Koonin [steven.koonin@gmail.com]; John Christy [climateman60@gmail.com]; Roy W. Spencer [roywspencer@hotmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]  
**Subject:** Re: edits to Chapter 12  
**Attachments:** 12.heat\_cold mortality.May6[SEK][RM].docx

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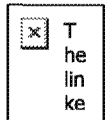
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## 12 Mortality from temperature extremes

Changes in temperature extremes are among the most certain impacts expected in a warming globe -- extreme heat events are expected to become more frequent while extreme cold events become less frequent. This pattern is evident in the historical period (as discussed in Section XX) and is expected to intensify with continued warming.

Mortality during heat extremes is typically caused by heat stroke and heat exhaustion, while mortality during cold extremes is typically caused by hypothermia and heart strain. It is well known that global mortality is substantially greater for extreme cold than for extreme heat.<sup>1,2</sup>

Specific to the U.S., extreme heat and extreme cold both kill hundreds of people each year.; however, different approaches to assessing heat/cold mortality produces different results. The Center for Disease Control (CDC) National Center for Health Statistics Compressed Mortality Database, which is based on death certificates, indicates that about twice as many people die of “excessive cold” conditions in a given year than of “excessive heat.”<sup>3,4</sup>

A 2015 epidemiological study of deaths in published in *The Lancet* found that cold-related deaths in the U.S. were about a factor of fifteen higher than heat-related deaths.<sup>5</sup> However, the study did not adjust for the seasonal cycle in mortality rates, which tend to increase during the winter months due to non-weather factors like influenza.<sup>6</sup> A more recent paper found that 86% of temperature-related deaths in the U.S. are due to cold-related mortality.<sup>7</sup>

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<sup>1</sup> Qi Zhao et al., “Global, Regional, and National Burden of Mortality Associated with Non-Optimal Ambient Temperatures from 2000 to 2019: A Three-Stage Modelling Study,” *The Lancet Planetary Health* 5, no. 7 (July 2021), [https://doi.org/10.1016/s2542-5196\(21\)00081-4](https://doi.org/10.1016/s2542-5196(21)00081-4).

<sup>2</sup> <https://ourworldindata.org/part-one-how-many-people-die-from-extreme-temperatures-and-how-could-this-change-in-the-future>

<sup>3</sup> Brett R. Scheffers et al., “The Broad Footprint of Climate Change from Genes to Biomes to People,” *Science* 354, no. 6313 (November 11, 2016): aaf7671, <https://doi.org/10.1126/science.aaf7671>.

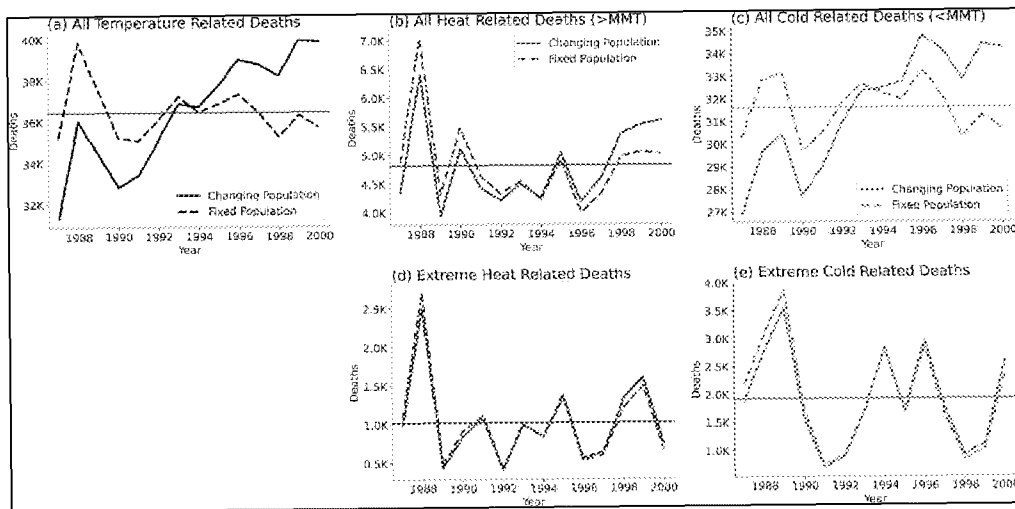
<sup>4</sup> Rachel H. Alinsky, Scott E. Hadland, J. Deanna Wilson, Pamela A. Matson, and Brendan Saloner, “Trends in Polysubstance Overdose Deaths Involving Opioids, Stimulants, and Benzodiazepines by Race and Ethnicity in the US, 2007-2021,” *JAMA Network Open* 7, no. 3 (March 2024): e238249, <https://doi.org/10.1001/jamanetworkopen.2024.8249>.

<sup>5</sup> Lancet Commission on Climate and Health, “Health and Climate Change: Policy Responses to Protect Public Health,” *The Lancet* 386, no. 10006 (November 7, 2015): 1861–1914, [https://doi.org/10.1016/S0140-6736\(15\)60854-6](https://doi.org/10.1016/S0140-6736(15)60854-6).

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<sup>7</sup> Tarik Benmarhnia et al., “Deaths Attributable to Heat and Cold: Comparison of Data Sources and Evaluation of Inconsistencies,” *GeoHealth* 8, no. 3 (March 2024): e2023GH000799, <https://doi.org/10.1029/2023GH000799>.





**Figure 12.1:** Time series of temperature-related deaths across all 106 cities. (a) The solid line represents total temperature-related deaths, while the dashed line indicates temperature-related deaths with a fixed population (average population from the 1987–2000 period). (b) Similar to (a), but for heat-related deaths. (c) Similar to (a), but for cold-related deaths. (d) Time series of deaths occurring in temperatures above the 97.5th percentile. (e) Similar to (d), but for temperatures below the 2.5th percentile. From <https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2023GH000799>

The IPCC AR6 Working Group 2 Chapter 16.2.3.5 states how heat-related mortality is declining over time:<sup>8</sup>

“Heat-attributable mortality fractions have declined over time in most countries owing to general improvements in health care systems, increasing prevalence of residential air conditioning, and behavioral changes. These factors, which determine the susceptibility of the population to heat, have predominated over the influence of temperature change.”

A 2011 study of 40 major US cities between 1975 and 2004, found that heat wave mortality had decreased, in spite of rising temperatures, due to adaptation.<sup>9</sup>

By reducing mortality from cold events and adapting to heat extremes, rising temperatures are associated with a net saving of lives.

It is both disappointing and telling to see how the IPCC misrepresents the situation in its AR6 Synthesis report. Section A.2.5 of that document states: “In all regions increases in extreme heat

<sup>8</sup> B. O'Neill et al., “Key Risks Across Sectors and Regions,” in *Climate Change 2022: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Geneva, CH: Intergovernmental Panel on Climate Change, 2021), 2411–2538.

<sup>9</sup> Keith T. Ingram, Carolyn W. Furman, and John W. Jones, “Climate Change Impact and Adaptation Assessment: A Guide for Coastal Resources Managers,” *Weather, Climate, and Society* 3, no. 4 (October 2011): 234–249, <https://doi.org/10.1175/WCAS-D-11-00055.1>.

events have resulted in human mortality and morbidity (*very high confidence*).” But it is silent on the larger decline of deaths during extreme cold events.

### *Mortality risks and energy costs*

A 2016 study of US long term mortality risks associated with temperature variations (Barreca et al. 2016 ) showed that increases in mortality across the US are associated both with cold weather and hot weather. But over time, the introduction of electricity and the adoption of central heating and air conditioning (AC) dramatically reduced both risks, especially those associated with hot weather. Prior to 1960, a day above 90°F (32°C) added 2.2 percent to the average mortality risk rate, but after 1960 the same weather added only 0.3 percent to mortality risk, an 85 percent reduction. Prior to 1960 temperatures below 39°F (4°C) added about 1 percent to mortality risk but after 1960 the same weather only added about half that amount. Adaptation through conventional household improvements dramatically reduced public vulnerability to weather extremes. The entire reduction in hot weather mortality was attributable to widespread adoption of indoor AC, which depended on the availability of reliable and affordable electricity.

The corollary of this finding is that the use of heating and cooling systems depends on energy being affordable. Doremus et al. (2022) showed that wealthy and poor households in the US adjust their energy expenditures at similar rates in response to moderate temperature swings, but not in response to extreme temperature swings. When temperatures swing to very cold levels (< 5°C) energy spending in high-income households rises by 1.2 percent but in low-income households by only 0.5 percent. On very hot days (>30°C) electricity spending in high-income households rises by 0.5 percent but does not change at all in low-income households. The latter result is observed even in subsamples where all households have AC. The implication is that even with widespread adoption of home heating and cooling systems, inability to afford energy leaves low-income households exposed to weather extremes.

Barreca, Alan, Karen Clay, Olivier Deschenes, Michael Greenstone, and Joseph S Shapiro, “Adapting to climate change: The remarkable decline in the US temperature mortality relationship over the twentieth century,” *Journal of Political Economy*, 2016, 124 (1), 105–159.

J.M. Doremus, I. Jacqz and S. Johnston (2022), “Sweating the energy bill: Extreme weather, poor households, and the energy spending gap.” *Journal of Environmental Economics and Management*, doi: <https://doi.org/10.1016/j.jeem.2022.102609> .

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**From:** Judith Curry <curry.judith@gmail.com>  
**Sent:** Tuesday, May 6, 2025 12:27 PM  
**To:** Steven Koonin  
**Cc:** Ross McKittrick; John Christy; Roy W. Spencer; Travis Fisher  
**Subject:** Re: edits to Chapter 12

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SEK



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**From:** Steven Koonin [steven.koonin@gmail.com]  
**Sent:** 5/6/2025 3:52:20 PM  
**To:** 'Ross McKittrick' [ross.mckittrick@gmail.com]; 'Judith Curry' [curry.judith@gmail.com]  
**CC:** 'John Christy' [climateman60@gmail.com]; 'Roy W. Spencer' [roywspencer@hotmail.com]; 'Travis Fisher' [travis.scott.fisher@gmail.com]  
**Subject:** edits to Chapter 12  
**Attachments:** 12.heat\_cold mortality.May6[SEK].docx

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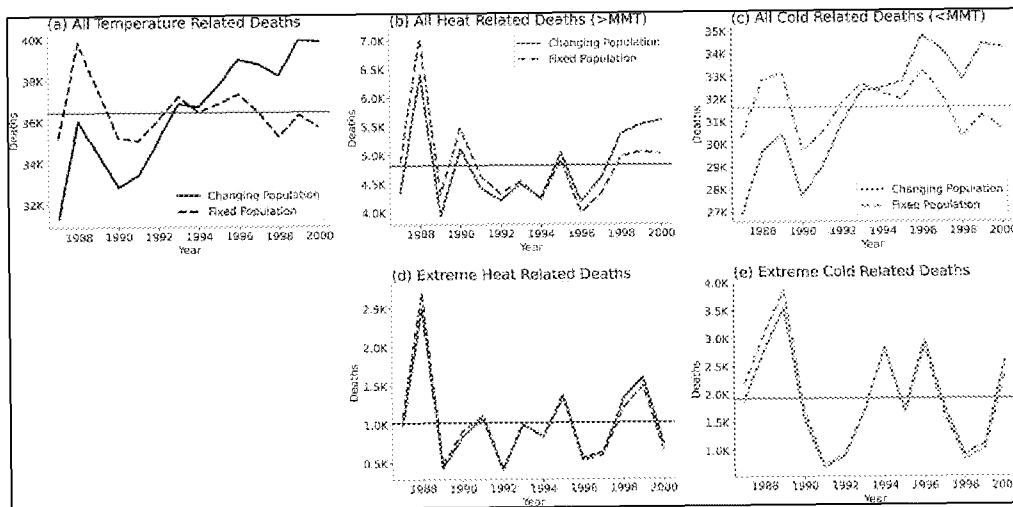
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**Caption:** Time series of temperature-related deaths across all 106 cities. (a) The solid line represents total temperature-related deaths, while the dashed line indicates temperature-related deaths with a fixed population (average population from the 1987–2000 period). (b) Similar to (a), but for heat-related deaths. (c) Similar to (a), but for cold-related deaths. (d) Time series of deaths occurring in temperatures above the 97.5th percentile. (e) Similar to (d), but for temperatures below the 2.5th percentile. From <https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2023GH000799>

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**From:** Judith Curry <curry.judith@gmail.com>  
**Sent:** Monday, May 5, 2025 4:14 PM  
**To:** John Christy; Steven Koonin; Ross McKittrick; Roy Spencer; Travis Fisher  
**Subject:** Ch 6 Attribution  
**Attachments:** 6 Attribution (1).docx

Attached is complete draft of Attribution chapter, i look forward to your suggestions

--



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## 6 Attribution challenges

### 6.1 Introduction

The detection and attribution process is concerned with assessing the causal relationship between one or more drivers and a responding system. The Intergovernmental Panel on Climate Change (IPCC) provides clear definitions for detection and attribution in climate science, based on their Sixth Assessment Report (AR6). These terms are crucial for understanding climate change impacts and are used to assess whether observed changes are significant and what caused them. As defined by the IPCC AR6 WGI Glossary (IPCC, 2025):

*Detection:* "Detection of change is defined as the process of demonstrating that climate or a system affected by climate has changed in some defined statistical sense, without providing a reason for that change. An identified change is detected in observations if its likelihood of occurrence by chance due to internal variability alone is determined to be small, for example, <10%."

*Attribution:* "Attribution is defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with a formal assessment of confidence."

The definition of detection emphasizes a statistical approach, focusing on whether changes are significant enough to stand out from natural variability without yet attributing causes.

The attribution process involves assessing how much human activities, such as industrial emissions, versus natural factors, like volcanic eruptions, contribute to observed changes, with a structured confidence level to reflect scientific certainty. Attribution requires the evaluation of the contributions of all external drivers to the system change.

While the IPCC's definitions are clear, there is ongoing scientific debate around attribution methods, particularly in attributing extreme weather events to climate change. The IPCC has long cautioned that methods to establish causality in climate science are inherently uncertain and ultimately depend on expert judgement. The Fourth Assessment Report: The Physical Science Basis (C Hegerl et al., 2007) explained it as follows:

'Attribution' of causes of climate change is the process of establishing the most likely causes for the detected change with some defined level of confidence... unequivocal attribution would require controlled experimentation with the climate system. Since that is not possible, in practice attribution of anthropogenic climate change is understood to mean demonstration that a detected change is 'consistent with the estimated responses to the given combination of anthropogenic and natural forcing' and 'not consistent with alternative, physically plausible explanations of recent climate change that exclude important elements of the given combination of forcings' (IPCC, 2001)... The approaches used in detection and attribution research described above cannot fully account for all uncertainties, and thus ultimately expert judgement is required to give a calibrated assessment of whether a specific cause is responsible for a given climate change.

The Fifth Assessment Report Working Group II makes the following statement: (W Cramer et al., 2014):

“Two broad challenges to the detection and attribution of climate change impacts relate to observations and process understanding. On the observational side, high-quality, long-term data relating to natural and human systems and the multiple factors affecting them are rare. In addition, the detection and attribution of climate change impacts requires an understanding of the processes by which climate change, in conjunction with other factors, may affect the system in question.”

Because of the complexity of the causal chains in the climate system, investigation of these relationships is exceptionally challenging.

## **6.2 Attribution methods**

The Intergovernmental Panel on Climate Change (IPCC) employs several attribution methods to assess the causes of observed climate changes, distinguishing between natural and human-induced factors. Below is a concise description of the key attribution methods that have been used by the IPCC:

*Optimal Fingerprinting* uses statistical techniques to compare observed climate data with climate model simulations of the responses to individual forcings (e.g., anthropogenic greenhouse gases, aerosols, natural forcings like solar variability). A regression model estimates the contribution of each forcing to observed changes, accounting for natural variability and model uncertainties.

*Pattern Correlation Methods* analyze spatial or temporal patterns of climate variables (e.g. temperature or precipitation) to identify similarities between observed changes and model-simulated responses to specific forcings. This method is useful for attributing shifts in atmospheric circulation or sea surface temperature patterns.

*Time Series Analysis* examines temporal changes in climate variables to attribute trends to specific forcings. This approach compares long-term observed trends to model simulations with and without anthropogenic forcings. This method helps distinguish between short-term natural variability (e.g., El Nino) and long-term anthropogenic signals.

*Multi-Step Attribution* connects changes to impacts and then to forcings. An example is linking greenhouse gas emissions to warming, warming to increased heatwaves, and heatwaves to specific societal impacts.

*Process-Based Attribution* focuses on understanding the physical mechanisms behind observed changes. This approach combines observations, climate models, and theoretical understanding to attribute changes in specific processes to forcings. This approach is often used for regional climate phenomena, such as monsoon changes or polar amplification

*Multi-Model and Ensemble Approaches* use multiple climate models (e.g. CMIP6 ensemble)

to account for uncertainties and improve confidence in attribution results. Large ensembles of simulations help separate the forced climate signal from internal variability.

*Extreme Event Attribution* assesses in the role of human influence in the likelihood of occurrence or intensity of extreme weather events (e.g. heat waves, droughts). Methods include:

- Fraction of Attributable Risk quantifies how much anthropogenic climate change has altered the probability of an event
- Probabilistic Event Attribution uses large ensembles of climate model simulations to compare event likelihood in a world with and without human influence
- Storyline Approach examines the physical processes driving an event and evaluates how anthropogenic forcings modified those processes

### 6.3 Attribution of global warming

Attribution statements for global warming in the three most recent IPCC Assessment reports are:

AR4: “Most of the observed increase in global average temperatures since the mid-20<sup>th</sup> century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations.” (IPCC, 2007)

AR5: “It is *extremely likely* that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together. The best estimate of the human-induced contribution to warming is similar to the observed warming over this period.” (IPCC, 2013)

AR6: “The *likely* range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019 is 0.8°C to 1.3°C, with a best estimate of 1.07°C. It is *likely* that well-mixed GHGs contributed a warming of 1.0°C to 2.0°C, other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C, natural drivers changed global surface temperature by –0.1°C to +0.1°C, and internal variability changed it by –0.2°C to +0.2°C. It is *very likely* that well-mixed GHGs were the main driver of tropospheric warming since 1979.” (IPCC, 2021)

The AR4 and AR5 attribution statements reference the warming to the mid-20<sup>th</sup> century, the period when greenhouse gas emissions began rapidly increasing. The words “most” and “more than half” are deliberately imprecise, potentially ranging from 51 to 99% of the warming – presumably this imprecision is to account for structural uncertainties such as natural internal variability. The confidence level increases from *very likely* to *extremely likely* from AR4 to AR5. The structure of the attribution statement in the AR6 is fundamentally different, referencing the warming to the period 1850-1900. The AR6 attribution statement is more precise numerically, but with a lower level of confidence at “likely” – the AR6 attributes essentially all of the warming to increases in greenhouse gases. The most confident statement from the AR6 relates to the tropospheric warming since 1979, using the words “main driver” and “*very likely*.”

There are two areas of substantive criticism of the IPCC assessment of the causes of the recent warming: inadequate assessment of natural climate variability, and inappropriate statistical methods. Both of these issues are relevant not only in context of the main policy-relevant statement of the IPCC concerning attribution of the recent warming, but also because the global warming attribution provides the basis for extreme event attribution

### ***6.3.1 Natural climate variability***

The IPCC AR6 states that natural external drivers since 1850-1900 have changed global surface temperature by  $-0.1^{\circ}\text{C}$  to  $+0.1^{\circ}\text{C}$ , and internal variability has changed it by  $-0.2^{\circ}\text{C}$  to  $+0.2^{\circ}\text{C}$  – on average, having essentially no net impact on the warming since 1850-1900. This assessment of the contributions of natural variability has been disputed by a number of publications that question the magnitudes of the contributions from solar forcing and internal variability from the large-scale ocean circulations (R Connolly et al., 2021; W Soon, 2023).

If the Equilibrium Climate Sensitivity to  $\text{CO}_2$  is low (REF PREVIOUS CHAPTER), then natural climate variability becomes more important in the attribution of the recent warming. Further, if natural variability is higher, then estimates of the Equilibrium Climate Sensitivity from the historical period would be lower (Scafetta, 2023).

#### *Solar variability*

The IPCC AR5 concluded that the best estimate of radiative forcing due to Total Solar Irradiance (TSI) changes for the period 1750–2011 was  $0.05 \text{ W/m}^2$  (Myrhe et al., 2014). The IPCC AR6 acknowledges a much larger range of estimates of changes in TSI over the last several centuries, stating that the TSI between the Maunder Minimum (1645–1715) and the second half of the twentieth century increased by  $0.7\text{--}2.7 \text{ W/m}^2$ , a range that includes both low and high variability TSI data sets (Gulev, 2021). However, the recommended forcing dataset for the CMIP6 climate model simulations used in the AR6 for attribution studies averages two data sets with low solar variability (Matthes, 2017).

While the IPCC AR6 shows a substantially greater solar impact than does the AR5, the overall impact on the climate was assessed to be small compared to anthropogenic forcing of climate change. However, the impact of solar variations on the climate is uncertain and subject to substantial debate - something that you would not infer from the IPCC assessment reports (Lockwood, 2012; Connolly et al., 2021).

Exactly how TSI has changed over time has been a challenging problem to resolve. Since 1978, there have been direct measurements of TSI from satellites. However, the data exhibit non-negligible inconsistencies, and interpreting any multi-decadal trends in TSI requires comparisons of observations from overlapping satellites. Substantial uncertainty exists in the TSI composites, particularly owing to a gap in coverage during 1989 to 1992 that prevented direct cross-calibrations between two successive satellites (N Scafetta, 2019). This rather arcane issue of cross-calibration of two satellite records has profound implications. There are a number of rival composite TSI datasets, disagreeing as to whether TSI increased or decreased during the period 1986–96 (the ACRIM gap; see Chapter 4). Further, the satellite record of TSI is used for calibrating proxy

models, whereby past solar variations are inferred from sunspots and cosmogenic isotope measurements (Velasco Herrera et al., 2015).

There is substantial evidence for high solar activity in the second half of the 20<sup>th</sup> century (starting in 1959) and extending into the 1990's, before a decline in the early 21<sup>st</sup> century; this period is often termed the "Modern Maximum." (Chatzistergos et al., 2023; Solanki et al., 2004; Usoskin et al., 2007). However, some scientists have concluded that it is not possible to be confident of any multi-decadal trend in TSI (Schmutz, 2021).

As a result of this uncertainty, some reconstructions for past values of TSI (since 1750) have low variability, implying a very low impact of solar variations on global mean surface temperature, whereas datasets with high TSI variability can explain more than 70% percent of the temperature variability since preindustrial times (Scafetta, 2013; Stefani, 2021). Hence, the choice of which TSI satellite record used in an analysis can substantially influence how much climate change is attributed to human versus natural forcings.

~~A review article on this topic was recently published in the journal *Research in Astronomy and Astrophysics* (Connolly et al., 2023). The article had 23 co-authors with a range of perspectives, but who were united by their agreement not to take the consensus approach of the IPCC. Rather, the paper emphasized where dissenting scientific opinions exist as well as identifying areas where there is scientific agreement. The authors found that the Sun/climate debate is an issue where the IPCC's consensus statements were prematurely achieved through the suppression of dissenting scientific opinions.~~ **MOVE TO CH 4**

There is growing evidence that other aspects of solar variability, which are referred to as solar indirect effects, amplify TSI forcing or are independent of TSI forcing. Scafetta et al. (2023) suggests that ~80% of solar influence on climate may stem from non-TSI mechanisms. Candidate processes include: solar ultraviolet changes; energetic particle precipitation; atmospheric-electric-field effect on cloud cover; cloud changes produced by solar-modulated galactic cosmic rays; large relative changes in the magnetic field; and the strength of the solar wind. Solar indirect effects are not included in climate models, although indirect methods of estimating these effects suggest significant influence. However, claims of non-TSI mechanisms influencing climate are uncertain and debated.

#### *Natural variability of large-scale ocean circulations*

Variations in global mean surface temperature are linked to recurrent large-scale variations in ocean circulation patterns. These circulation patterns include the Atlantic Multidecadal Oscillation (AMO), the Pacific Decadal Oscillation (PDO) and the El Nino-Southern Oscillation (ENSO). These circulation patterns influence ocean heat uptake and heat distribution, and also influence atmospheric circulation patterns and cloud distributions. There is some debate as to whether these variations are strictly internal to the climate system, or whether this variability can have a solar/astronomical origin or can be influenced by large volcanic eruptions.

While climate models simulate the large-scale ocean circulations and internal climate variability,

the simulated magnitude in the multi-decadal band is too low in most models relative to observations, and the phasing of the variability in long-term climate simulations is not synced with the actual, observed climate variations. Averaging multiple simulations from climate models effectively averages out the internal variations, leaving only the forced climate variability (e.g., CO<sub>2</sub> forcing). With most of the modern warming beginning in the late 1970's, the recent 50-year warming is on the same time scale as the multi-decadal oscillations of the AMO and PDO.

Here are summary statements from the IPCC AR5 and AR6 reports:

“Decadal variability in the Pacific, associated with the PDO or IPO, contributes significantly to regional and global temperature trends, but the relative contributions of internal variability and external forcing are difficult to disentangle in CMIP5 simulations.” (IPCC, 2013)

"Since AR5, there has been increased understanding of the role of internal variability, such as ENSO, PDO, and AMO, in modulating regional climate trends. However, limitations in simulating the exact timing and amplitude of these modes in CMIP6 models contribute to uncertainties in attributing observed changes to anthropogenic forcing (high confidence)." (IPCC, 2021)

The amplitude of the peak-to-trough impact of the multi-decadal oscillations on global temperatures has been assessed by the IPCC AR6: “The likely range of change due to internal variability is -0.2°C to +0.2°C (IPCC, 2021).” This implies a trough-to-peak change of 0.4°C. Over many centuries, any global temperature changes from the troughs and peaks will cancel out, with little to no net impact.

However, with a nominal timescale of 60-80 years for oscillations such as the AMO and PDO, the timing of the peaks and troughs can be confused with the secular trend. This becomes very relevant for attributing the warming for the 50 years since 1975, during which most of the warming has occurred. Even if climate models have the correct amplitude of the multidecadal oscillations, the timing of the peaks and troughs is not adequately simulated, with each model and individual ensemble simulating a different phasing. Once the simulations of the ensemble members and different models are averaged, the natural internal variability contribution is averaged out, effectively cancelling the role of natural internal variability in the attribution process.

The Great Pacific Climate Shift of 1976-1977 was a notable climatic event characterized by an abrupt change in the North Pacific Ocean's atmosphere-ocean system that interacted with global climate patterns. This shift is closely associated with the Pacific Decadal Oscillation (PDO) that oscillates between warm and cool phases over decades. The 1976 shift marked a transition from a predominantly negative (cool) PDO phase (1947–1976) to a positive (warm) phase (1977 through 2000), with significant implications for global and regional climate patterns including the frequencies of El Nino and La Nina events. The Great Pacific Climate Shift coincided with the beginning of a period of accelerated global warming (REF TO A FIG OF GLOBAL TEMP ANOMALIES ELSEWHERE IN DOC) When the Great Pacific Climate Shift is accounted for in climate attribution analyses since 1950, it has been found that 40 percent or more of the warming

in the second half of the 20<sup>th</sup> century was caused by natural internal variability (McLean et al., 2009; Tung and Zhou, 2013; Chylek et al., 2016; Scafetta, 2021).

### **6.3.2 Statistical methods**

Optimal fingerprinting is a statistical technique that compares observed climate data with climate model simulations to identify patterns (or "fingerprints") associated with human influence. Optimal fingerprinting has been heavily used in the climate literature for establishing attribution; studies applying it have been cited thousands of times, and it has been prominently featured by the IPCC since the Third Assessment Report in 2001.

A series of papers by McKittrick has challenged the statistical methods commonly used in optimal fingerprinting and broader attribution analyses, based on commonly adopted practices in econometrics. These critiques highlight potential biases that could lead to over- or under-estimation of human influence on climate, and problems with the method that reduce confidence in the analysis results.

McKittrick (2022) challenged the methodology introduced by Allen and Tett (1999) for climate change attribution, which is a cornerstone of optimal fingerprinting. McKittrick argues that this methodology violates key conditions of the Gauss-Markov theorem, particularly the requirement that the conditional expectation of errors must be zero. This violation leads to biased and inconsistent estimates of attribution, undermining the reliability of the method.

McKittrick et al. (2023) addresses a paradox in climate attribution studies: standard trend models assume stationary (mean-reverting) error terms, while the climate econometrics literature suggests that if anthropogenic forcing is dominant, temperature trends should exhibit nonstationary (unit root) error terms, which could serve as a "fingerprint" for human influence. McKittrick and co-authors use tools from time series econometrics to resolve this issue, formalizing a hypothesis that temperature series contain both a nonstationary forcing component (due to anthropogenic influences) and a stationary "weather noise" component. This combination can bias unit root tests toward over-rejection, leading to misinterpretations in attribution studies.

McKittrick (2024) addresses the concern that for more than 20 years climate scientists—virtually alone among scientific disciplines—have used Total Least Squares (TLS) to estimate anthropogenic greenhouse gas signal coefficients, despite its tendency to be unreliable unless some strong assumptions hold that in practice are unlikely to be true. Under conditions which easily arise in optimal fingerprinting for climate attribution, TLS yields estimates with large positive biases. Thus, any study that has used TLS for optimal fingerprinting without verifying that it is appropriate in the specific data context has likely overstated the result.

While these analyses do not prove that all of the results from using these methods are wrong, it does show that the basis on which they were believed to be correct is non-existent – hence reducing confidence in the results. McKittrick's work underscores the importance of statistical rigor in attributing climate changes and the need to bridge the gap between econometric and climatological approaches.

## 6.4 Extreme event attribution

The IPCC AR6 provides an ambiguous assessment of the role of global warming in the historical record of extreme weather and climate events. Chapter 11 of WG1 states (Seneviratne et al., 2021):

“Evidence of observed changes in extremes and their attribution to human influence (including greenhouse gas and aerosol emissions and land-use changes) has strengthened since AR5, in particular for extreme precipitation, droughts, tropical cyclones and compound extremes (including dry/hot events and fire weather). Some recent hot extreme events would have been extremely unlikely to occur without human influence on the climate system.”

By contrast, Chapter 12 of WG1 (Table 12.12) paints a different picture – presumably, the expert judgment of different groups of authors for the two chapters came to different conclusions (Ranasinghe, 2021):

- High confidence in an increase in extreme heat events in tropical regions where observations allow trend estimation and in most regions in the mid-latitudes, medium confidence elsewhere
- Medium confidence in a decrease in extreme cold events in Australia, Africa and most of northern South America where observations allow trend estimation
- No evidence of emergence in the historical period of a change in river floods, heavy precipitation, drought, fire weather, severe wind storms, and tropical cyclones

While the overall issue of detecting changes in extreme weather events and their attribution remains ambiguous, most of the activity in this area relates to the attribution of single extreme weather events. The most prominent effort is the World Weather Attribution (WWA; [worldweatherattribution.org](http://worldweatherattribution.org)), which is an international research initiative that focuses on extreme event attribution, analyzing how climate change influences the likelihood and intensity of extreme weather events. The approach used by the WWA runs large ensembles of regional climate models to compare the event in today's climate, versus a pre-industrial climate without human-caused warming. WWA plays a significant role in linking extreme weather to climate change, using rapid probabilistic attribution to inform public and policy discussions.

However, the WWA's non-peer-reviewed reports, funding ties, and methodological challenges have sparked controversies, with critics questioning the robustness and impartiality of its conclusions. Despite these issues, WWA's work continues to shape climate science and media narratives. Technical criticisms of the approach include: neglect of a formal detection process; an implicit assumption that 100% of the post-industrial warming is caused by CO<sub>2</sub>; and failure to adequately account for natural internal climate variability.

Beyond the issues raised by event attribution approaches, there exist major challenges to the detection step – a step that is commonly skipped, contra to the IPCC's established detection and attribution approach. Extreme events are by definition rare. Many analyses of extreme event types (including the US National Assessment Reports) only evaluate data since 1950 or 1970. However, as emphasized by Chapter xxx, many of the worst extreme weather and climate events in U.S. history occurred in the first half of the 20<sup>th</sup> century and the 19<sup>th</sup> century. And if paleoclimate



reconstructions are also considered, it becomes very difficult for an event to pass the detection thresholds of exceeding what is expected from natural variability, particularly if a reasonably sized geographic region is considered.

In spite of these concerns, the U.S. is presently considering something like the WWA, which is being investigated by a NASEM Panel on Attribution of Extreme Weather and Climate Events and their impacts (NASEM, 2025).

Extreme weather events can be extreme in terms of the magnitude of individual events, the frequency of events crossing some threshold, or clustering of extreme events. It needs to be acknowledged that extreme events are by definition rare, and short historical records (even century long records) are insufficient for formulating meaningful statistics about return times and event likelihood.

Case studies from two recent high impact extreme events in the U.S. are provided to illustrate the challenges and ambiguities in attributing the frequency and intensity of extreme weather events to human-caused warming.

#### ***6.4.1 Case study – 2021 Western North America heat wave***

The 2021 Western North America heat wave was an extreme heat wave that affected much of Western North America in late June 2021. In particular, surface temperature records were set in Portland, OR (116°F; previous record 107°F) and Seattle, WA (108 °F; previous record 103°F) (Mass et al., 2024).

The WWA provided the following attribution statements (WWA, 2021; Philip et al., 2022):

- Based on observations and modeling, the occurrence of this heatwave was virtually impossible without human-caused climate change.
- The event is estimated to be about a 1 in 1000-year event in today's climate.
- The event would have been at least 150 times rarer without human-induced climate change.
- This heatwave was about 2°C hotter than it would have been if it had occurred at the beginning of the industrial revolution (when global mean temperatures were 1.2°C cooler than today).

Mass et al. (2024) summarizes the proximate sequence of compound events leading to the heat wave. There was a record-breaking midtropospheric ridge over the Pacific Northwest, forced by a tropical disturbance in the western Pacific. This produced record-breaking midtropospheric temperatures, strong subsidence in the lower atmosphere, low-level easterly flow that produced downslope warming on regional terrain and the removal of cooler marine air, and an approaching low-level trough that enhanced downslope flow. The event occurred at a time of maximum solar insolation, and drier-than-normal soil moisture. Using a storyline approach, Mass et al. assessed that there is no trend in drought and dry soils in the Pacific Northwest; there is no evidence of global warming producing stronger ridges of high pressure, and no observed trend in heat waves or record temperatures in the region. They concluded that although anthropogenic warming may

have contributed as much as 2°F to the magnitude of the event, there is little evidence of further amplification of the event from increasing greenhouse gases.

A more sophisticated statistical analysis of a model-based attribution study of this heat wave was conducted by Bercos-Hickey et al. (2022). Because this event is a far outlier and far above the bounds of Generalized Extreme Value distributions fitted from historical data, they concluded that estimates of return times, quantitative changes in event magnitude and frequency, and probability of the extreme temperatures such as provided by the WWA are not accurate and should be interpreted as having low confidence. They found that hindcast attribution methods using an ensemble of regional climate models, combined with Pearl (2009) causal inferences, can provide limited and conditional information about the magnitude of the human influence on this heatwave – they provided a more highly constrained estimate that human activities caused a ~1.4°C–1.8°F increase in the daily maximum temperatures.

The 2021 Western North America heatwave was a rare and unprecedented compound weather event, that broke century-old temperature records by as much as 9°F. While there is little doubt that anthropogenic global warming contributed to the probability and magnitude of the extreme temperatures, the uniqueness of the event challenges quantifying this influence by traditional event attribution methods.

Van Oldenborgh et al. (2022) summarize the challenges of attributing heat waves. A warming climate means that a fixed temperature threshold is passed more frequently, hence the probability of extreme heat increases. Land use changes, vegetation change, irrigation, air pollution, and other changes also drive changes in local and regional heatwaves trends. Sometimes these factors enhance heatwave intensity, but they can also counteract the effects of climate change. Temperature variability is unrealistic represented in many climate models, and does not stand up to standard quality assessments. Accordingly, heatwave attribution remains unreliable and a major scientific challenge in many regions. This is particularly true where the moisture budget is not well simulated, and where land surface changes have occurred.

#### **6.4.2 Case study – Hurricane Harvey rainfall** *IDON'T LOVE THIS EXAMPLE. DELETE? MAYBE SOMETHING ELSE?*

Hurricane Harvey made landfall in southern Texas on August 24, 2017 as a Category 4 hurricane. The primary damage from Harvey occurred after the storm had been downgraded to a tropical storm and stalled near the coastline with a stationary front along the TX/LA border, dropping torrential and unprecedented amounts of rainfall over Texas. Hurricane Harvey provides an informative example of the challenges of detection for a rare event, and also the complexity of extraneous factors that can influence such an event.

The first issue to consider is detection. Harvey set the record for most amount of rainfall from a continental U.S. landfalling hurricane (60 inches), going back at least to the 1880's when comprehensive records begin (Landsea, 2017). The previous top four rainfall producers for U.S. landfalling tropical cyclones were: 48 inches in Texas from Tropical Storm Amelia (1978), 45 inches in Florida from Hurricane Easy (1950), 45 inches in Florida from Tropical Storm Claudette (1979), and 40 inches in Texas from Tropical Storm Allison (2001). Looking more broadly at North

Atlantic hurricanes that made landfall in Central American and the Caribbean, Roth (2017) identifies the following landfalling hurricanes that produced more rainfall than Harvey: 100 inches in Cuba from Hurricane Flora (1963), 96 inches in Jamaica from the November 1909 Hurricane, 63 inches in Nicaragua from Hurricane Mitch (1998), and 62 inches in Mexico from Hurricane Wilma (2005). Hurricane Harvey's rainfall arguably meets the detection criteria, whereby an attribution analysis is justified, although Harvey's rainfall was far from unprecedented from historic Atlantic hurricane landfalls.

In addressing the attribution of extreme rainfall from a landfalling hurricanes, there are several factors leading to excessive rainfall that aren't associated with temperature. Slow motion of the hurricane near landfall can lead to high amounts of local rainfall (e.g. Wilma – 2005; Harvey – 2017;). Mountains/hills near the coast magnify rainfall potential due to forced upslope flow (e.g. Mitch – 1998). Upper-level troughs and cold fronts can lead to excessive rainfall (e.g. Floyd – 1999). Horizontally large tropical cyclones have larger rain footprints, which can lead to excessive rainfall owing to the longer time frame over which rainfall falls at any one location.

The WWA attribution analysis of Hurricane Harvey's rainfall (GJ van Oldenburgh et al., 2017) found that human-caused climate change made the heavy rainfall associated with Hurricane Harvey roughly three times more likely and 15% more intense.

Several publications based on model simulations have concluded that as much as 40% of the rainfall from Hurricane Harvey was caused by human-caused global warming (Emanuel 2017; Risser and Wehner 2017). The rationale for these assessments was that prior to the beginning of summer of 2017, sea surface temperatures in the western Gulf of Mexico exceeded 86°F and ocean heat content was the highest on record in the Gulf of Mexico (Trenberth et al., 2018). However, El Niño–Southern Oscillation (ENSO) and Atlantic circulation patterns contributed to this elevated heat content.

Landsea (2017) summarizes the arguments for more rainfall from tropical cyclones traveling over a warmer ocean. Simple thermodynamic calculations suggest that the amount of rainfall in the tropical latitudes would increase by about 4% per °F of sea surface temperature increase. Examining a 300-mile radius circle for nearly all of the rain implies that about 10% more total hurricane rainfall for a warming of 2-2.5°F. The Gulf of Mexico has warmed about 0.7°F since 1960. Even if it is assumed that all of this warming is due to manmade global warming, this suggests that roughly 3% of hurricane rainfall today can be reasonably attributed to manmade global warming. Hence, only about 2 inches of Hurricane Harvey's 60 inches can be linked to manmade global warming.

Aryal et al. (2018) examined the contribution of North Atlantic hurricanes to flooding and heavy rainfall across the continental U.S. Their analysis does not point to any significant changes in the magnitude or frequency of floods. They found that the North Atlantic Oscillation (NAO) plays a significant role in hurricane-related extreme rainfall along the U.S. East Coast, while ENSO is most strongly linked to the hurricane-related precipitation in Texas.

With regards to the rainfall associated with landfalling hurricanes, there is no clear signal of increasing rainfall owing to the complexity of the factors contributing to hurricane-induced rainfall.

## 6.5 Summary

There is an ongoing scientific debate around attribution methods, particularly in attributing extreme weather events to climate change. The IPCC has long cautioned that methods to establish causality in climate science are inherently uncertain and ultimately depend on expert judgement.

There are two areas of substantive criticism of the IPCC assessment of the causes of the recent warming: inadequate assessment of natural climate variability, and inappropriate statistical methods.

Detection of extreme weather events is challenged by their rarity, requiring a long data set and a choice of region and spatial scale to evaluate their occurrence against the background of natural weather and climate variability.

The most robust attribution statements for an extreme event relate to an incremental change (e.g. a temperature change in degrees or percent change in rainfall). Statements related to return times, quantitative changes in event magnitude and frequency, and probability of the extremes are not accurate owing to an inadequate amount of data, and are made with low confidence. There is no evidence in a change of weather or climate regime patterns from increasing greenhouse gases that would amplify or dampen extreme weather events, beyond basic thermodynamic considerations.

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**From:** Steven Koonin [steven.koonin@gmail.com]  
**Sent:** 5/6/2025 11:48:42 PM  
**To:** 'Judith Curry' [curry.judith@gmail.com]; 'Ross McKittrick' [ross.mckittrick@gmail.com]  
**CC:** 'Roy Spencer' [roywspencer@hotmail.com]; 'John Christy' [climateman60@gmail.com]; 'Travis Fisher' [travis.scott.fisher@gmail.com]  
**Subject:** RE: My suggested edits of Chapter 10  
**Attachments:** image001.jpg

Agreed - SEK

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**From:** Judith Curry <curry.judith@gmail.com>  
**Sent:** Tuesday, May 6, 2025 5:53 PM  
**To:** Ross McKittrick <ross.mckittrick@gmail.com>  
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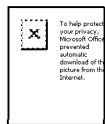
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## 10. Climate change and US agriculture

### 10.1 Econometric analyses

Econometric analyses of the effects of climate change on agriculture have sought to integrate information about long term crop yield changes in response to temperature and precipitation changes under assumptions about adaptive behavior by farmers. One method focuses on variations in agricultural land values. The rationale is that if climate change is a long-term net benefit for agriculture it should translate into higher market values for agricultural land, and vice versa. While individual crops might benefit from or be harmed by climate change, once the adaptive responses of farmers are taken into account the value of farmland represents an index of whether the changes are expected to be beneficial or not. Mendelsohn et al. (1994) examined the relationship between historical climatic variations on agricultural land values and concluded global warming would be slightly beneficial to American agriculture.

The Mendelsohn et al. method, called Ricardian analysis after David Ricardo, the 19<sup>th</sup> century British economist who pioneered the study of land values, attracted subsequent criticism from authors who argued it failed to account for differences in land values attributable to fixed locational characteristics like soil quality, and non-climatic changes including nearby urbanization. Deschênes and Greenstone (2007) looked at agricultural profits instead of land values and reached similar conclusions to Mendelsohn et al. (1994), namely that past climatic variations had relatively little effect on farm profitability and that warming would likely yield small overall benefits for the US agricultural sector. However a subsequent exchange with critics led them (Deschênes and Greenstone 2012) to revise their conclusions and project potentially large losses in US agriculture due to climate warming. Burke and Emerick (2016) looked at temperature variations over 1980 to 2000 and argued that farmers were not as able to adapt to temperature changes as the Ricardian method assumes and that climate change would have large negative impacts on corn and soy yields. Schlenker and Roberts (2009) similarly argued that yield gains to past warming would not carry over to the future and corn and soy yields would sharply decrease this century due to climate change.

Two recent studies have argued that pessimistic findings such as these are not robust. Ortiz-Bobea (2019) argued that land values aggregate farm and non-farm influences and the latter need to be filtered out. He developed a data set using cash rents for agricultural activity as a measure of land value specifically for farming activity. Whereas the land value model implied future losses under climate warming, the same model estimated using cash rents did not, leading the author to conclude the pessimistic results were due to using an inaccurate measure of the returns to farming activity. Bareille and Chakir (2023) assembled a large data base on farm sale prices in France for properties that sold twice between 1996 and 2019. They could replicate pessimistic results showing negative effects of warming on agricultural land values using conventional econometric modeling. But by taking advantage of the repeat sales data, which provides information on site-specific changes in land prices, they found the results reversed and implied that climate change will be very beneficial for French agriculture. The authors concluded that, taking adaptation into account, a warming climate would yield positive benefits for French agriculture that were between two and 20 times larger than had previously been estimated. On average, with full adaptation, they concluded that climate changes under the medium RCP4.5 scenario could double the value of French farmland by 2100.

A major deficiency of all these studies, however, is that they omit the role of CO<sub>2</sub> fertilization. Climate change as it relates to this report is caused by GHG emissions, chiefly CO<sub>2</sub>. The econometric analyses referenced above focus only on temperature and precipitation changes and do not take account of the beneficial growth effect of the additional CO<sub>2</sub> that drives them. As explained in Chapter 2 CO<sub>2</sub> is a

major driver of plant growth so this omission biases the analysis towards underestimation of the benefits of climate change on agriculture.

## 10.2 Field studies of CO<sub>2</sub> enrichment

One of the ways the effect of CO<sub>2</sub> on crop growth has been studied is through “free air enrichment experiment” or FACE plots, in which small chimneys are placed in fields surrounding plants and the growth response to elevated CO<sub>2</sub> under varying weather conditions are recorded. Ainsworth et al. (2020) summarizes results from about 250 such studies. They found that elevation of CO<sub>2</sub> by 200 ppm cause an average 18% increase in crop yield in C3 plants. C4 plants exhibited benefits mainly under drought conditions.

In addition to FACE plot experiments there have been thousands of laboratory experiments on the effects of CO<sub>2</sub> on all kinds of plant growth. Here we review some of the results on key US agricultural crops.

### *Soybean*

Studies on the impact of elevated CO<sub>2</sub> on Soybean (*Glycine max* (L.) Merr.) plants in the water-deficient region of Huang-Huai-Hai Plain, China, showed that elevated CO<sub>2</sub> concentrations resulted in improved photosynthesis rate, water use efficiency and growth (Li, 2013) under both normal conditions and drought conditions. The CO2Science.org website reports on 108 published experiments between 1985 and 2019 exposing soybean to enriched CO<sub>2</sub> levels. Converted to a +300ppm common scale the average growth benefit was +50.9 percent. In addition there were 10 studies reporting on +600 ppm CO<sub>2</sub> enrichment, resulting in an average increase in photosynthesis of 90.3%.

### *Maize (corn)*

The CO2Science.org website reports on 28 published experiments between 1983 and 2018 exposing corn (*Zea mays* L.) to enriched CO<sub>2</sub> levels. Converted to a +300ppm common scale the average growth benefit was +23.7 percent. Corn also benefits from increased drought tolerance under elevated CO<sub>2</sub>. An experimental study (Allen Jr, 2011) exposed plants to water stress conditions in sunlit controlled-environment chambers at 360 ppm (ambient) and 720 ppm (elevated) CO<sub>2</sub>. The drought stress caused a 41% loss of growth under ambient CO<sub>2</sub> but only a 13% loss under elevated CO<sub>2</sub>.

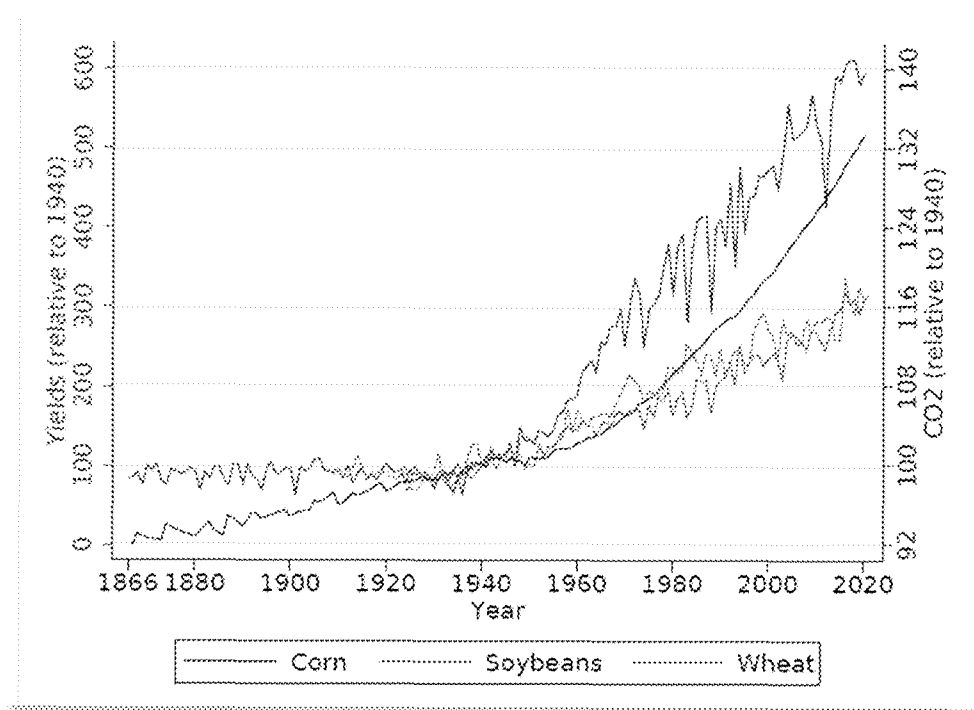
### *Wheat*

The CO2Science.org website reports on 92 published experiments between 1983 and 2020 exposing common wheat (*Triticum aestivum* L.) to enriched CO<sub>2</sub> levels. Converted to a +300ppm common scale the average growth benefit was +67.6 percent. Blandino (2020) measured the yield as well as nutritional quality of an “improver” hybrid wheat variety and its parents under elevated CO<sub>2</sub> levels (+166 ppm). They reported a grain yield increase of +16% but a 7% decrease in grain protein levels. But they found that the food quality of different wheat varieties responded differently to elevated CO<sub>2</sub> levels, so that with proper varietal selection end-users can select wheat types that best take advantage of the elevated CO<sub>2</sub>.

### *Further evidence*

A 2021 report from the US National Bureau of Economic Research (Taylor and Schlenker 2021) used satellite-measured observations of outdoor CO<sub>2</sub> levels across the United States, matched to county-level agricultural output data and other economic variables. After controlling for the effects of weather, pollution and technology the authors concluded that CO<sub>2</sub> emissions had boosted US crop production since 1940 by 50 to 80 percent, attributing much larger gains than had previously been

estimated using FACE experiments. They found that every ppm of increase in CO<sub>2</sub> concentration boosts corn yields by 0.5 percent, soybeans by 0.6 percent, and wheat by 0.8 percent.



**Figure 10.1:** US average CO<sub>2</sub> levels and yields of corn, soy and wheat all normalized so 1940=100.  
Source: Taylor and Schlenker (2021)

Beyond growth benefits, extra CO<sub>2</sub> boosts plant resilience to heat. Deryng et al. (2016) surveyed all available evidence regarding how wheat, maize, rice and soybean will grow under a combination of climate warming and rising CO<sub>2</sub> levels. They concluded that warming would, eventually, have a negative effect on plant growth but it would be fully compensated by the extra CO<sub>2</sub> for wheat and soybean, and almost fully for rice and maize. And as discussed in Chapter 2, plants use water more efficiently when there is more CO<sub>2</sub> in the air.

Deryng et al. (2016) surveyed evidence on crop water productivity (CWP), i.e. yield per unit of water used, drawing attention to the potential for CO<sub>2</sub> both to enhance photosynthesis and reduce leaf-level transpiration (water loss during leaf respiration). They surveyed all available FACE data on crop yield changes for Maize (corn), Wheat, Rice and Soybean, and combined it with crop model data simulating yield responses as of 2080 under the extreme RCP8.5 scenario in four growing regions (Tropics, Arid, Temperate and Cold) each of which were split into rainfed and irrigated sub-regions. In every region they reported that models without CO<sub>2</sub> fertilization predicted CWP losses but CO<sub>2</sub> fertilization more than offset them and once it was taken into account all regions showed a net CWP gain. Deryng et al (2016) also reported that negative impacts on wheat and soybean yields were fully offset by CWP gains, and mitigated by up to 90% for rice and 60% for maize.

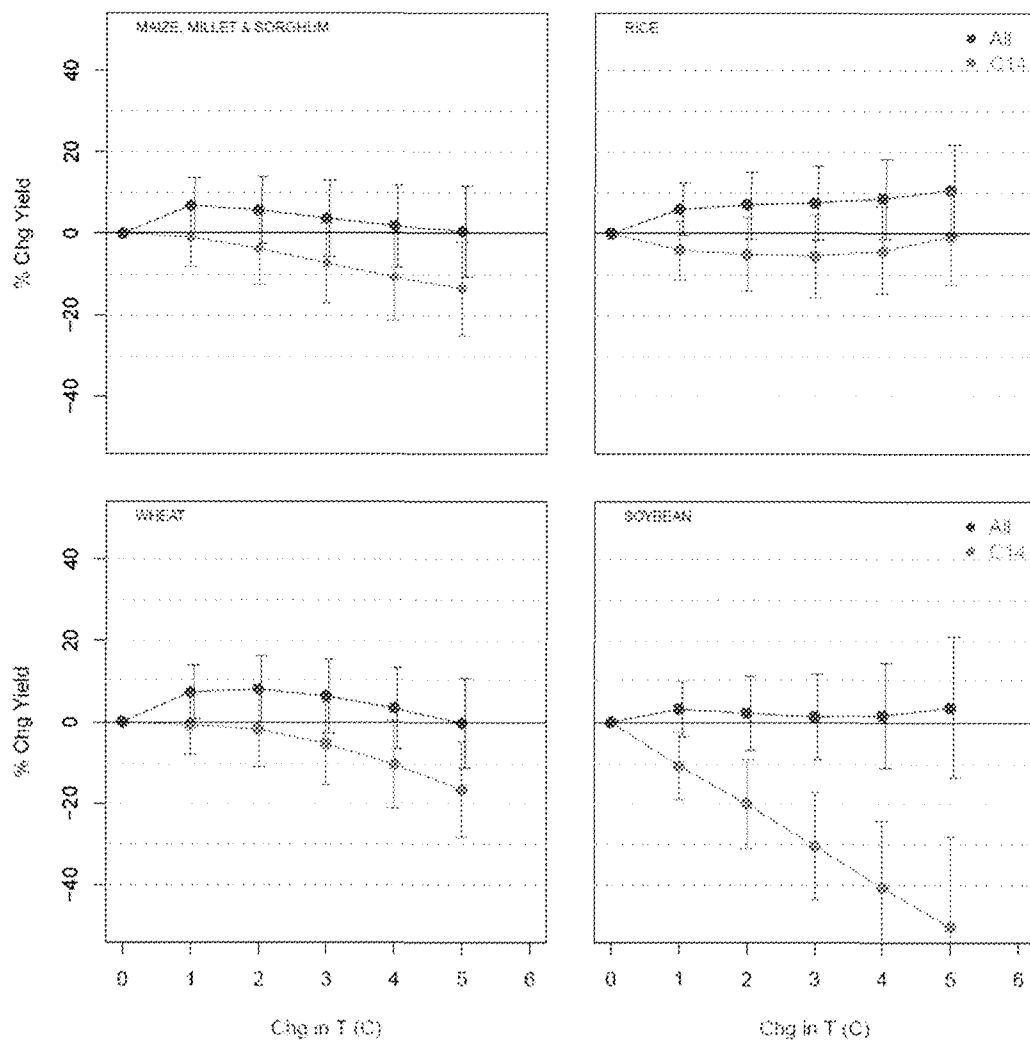
Similar to this, Cheng et al. (2017) noted that increased global plant growth from 1982 to 2011 due to rising CO<sub>2</sub> uptake was accompanied by such large gains in CWP that despite the extra biomass global water use by plants had not increased.

Deryng et al. (2016) assumed that climate change would “exacerbate water scarcity”. It is noteworthy that while models predict drylands will expand under climate warming, current data show the opposite: greening is happening even in arid areas. Zhang et al. (2014) report that due to increased CO<sub>2</sub> levels “increasing aridity in drylands won’t lead to a general loss of vegetation productivity”; increased desertification will happen in at most 4% of currently arid areas.

### **10.3 Crop modeling meta-analyses**

Notwithstanding the abundant evidence for the direct benefits of CO<sub>2</sub> and of CO<sub>2</sub>-induced warming on crop growth, in 2023 the US Environmental Protection Agency (EPA 2023) boosted its estimate of the Social Cost of Carbon (SCC) about five-fold based in large part on a very pessimistic 2017 estimate of global agricultural damages from climate warming (Moore et al., 2017). One of the two damage models used by the EPA attributed nearly half of the 2030 SCC to projected global agricultural damages based on the Moore et al. (2017) analysis. This study was a meta-analysis of crop model studies simulating yield changes for agricultural crops under various climate warming scenarios. Moore et al. projected declining global crop yields for all crop types in all regions due to warming.

McKittrick (2025) re-examined the Moore et al. database and found that, while it claimed to cover 1,722 studies, only half the entries ( $N=862$ ) had complete records, so that the sample available for regression analysis was much smaller than both studies indicated. McKittrick noted that the variable most commonly missing was the change in ambient CO<sub>2</sub> and found that in many cases these could be recovered from the underlying studies or the original climate scenario tables. He thereby increased the usable sample size by 40 percent. The crop yield projections incorporating the newly available data changed considerably. As shown in Figure 10.2, whereas the partial data set implied warming would decrease yield (blue lines), the complete data set implied constant or increase global yields, even out to 5°C warming (green lines).



**Figure 10.2** Crop yields under CO<sub>2</sub>-induced climate warming. Blue: as published in Moore et al. (2017). Green: after including omitted data. Source: McKittrick (2025).

In summary, there is abundant evidence going back decades that rising CO<sub>2</sub> levels benefit plants including agricultural crops, and that CO<sub>2</sub>-induced warming will be a net benefit to US agriculture. The warming since 1981, in combination with adaptive behaviour by farmers, has been beneficial on its own for maize. The increased ambient CO<sub>2</sub> has also boosted productivity of all major US crop types. Various attempts to argue that CO<sub>2</sub>-induced warming will harm agriculture do not hold up under scrutiny.

Deschênes, Olivier and Michael Greenstone (2007) *The Economic Impacts of Climate Change: Evidence from Agricultural Output and Random Fluctuations in Weather* *American Economic Review*. Feb 2007, Vol. 97, No. 1: Pages 354-385

Deschênes, Olivier and Michael Greenstone (2012) The Economic Impacts of Climate Change: Evidence from Agricultural Output and Random Fluctuations in Weather: Reply to Comment *American Economic Review*. 102, no. 7: 3761-3773. <http://hdl.handle.net/1721.1/82641>

Ortiz-Bobea, Ariel (2019) The role of nonfarm influences in ricardian estimates of climate change impacts on US agriculture. *American Journal of Agricultural Economics*. 102 (3), 934–959.

Schlenker, Wolfram and Michael Roberts (2009) Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. *Proceedings of the National Academy of Sciences* 106 (37) 15594-15598 <https://doi.org/10.1073/pnas.0906865106>

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**From:** Steven Koonin <steven.koonin@gmail.com>  
**Sent:** Tuesday, May 6, 2025 3:34 PM  
**To:** 'Roy Spencer'; 'John Christy'; 'Judith Curry'  
**Cc:** 'Ross McKittrick'; 'Travis Fisher'  
**Subject:** RE: My suggested edits of Chapter 10  
**Attachments:** ~WRD0412.jpg

There's a kernel of truth in that ...

SEK

---

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**Sent:** Tuesday, May 6, 2025 3:31 PM  
**To:** John Christy <climateman60@gmail.com>; Judith Curry <curry.judith@gmail.com>  
**Cc:** Steve Koonin <steven.koonin@gmail.com>; Ross McKittrick <ross.mckittrick@gmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>  
**Subject:** RE: My suggested edits of Chapter 10

John made a corny joke.

Sent from my Verizon, Samsung Galaxy smartphone

----- Original message -----

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**Date:** 5/6/25 2:28 PM (GMT-06:00)  
**To:** Judith Curry <curry.judith@gmail.com>  
**Cc:** Steve Koonin <steven.koonin@gmail.com>, Ross McKittrick <ross.mckittrick@gmail.com>, "Roy W. Spencer" <roywspencer@hotmail.com>, Travis Fisher <travis.scott.fisher@gmail.com>  
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All

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John C.

John Christy  
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Alabama State Climatologist

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climatemanager60@gmail.com

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<10 Climate and Agriculture.May6[SEK] CURRY.docx>



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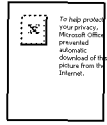
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**From:** Judith Curry [curry.judith@gmail.com]  
**Sent:** 5/6/2025 4:42:38 PM  
**To:** Steven Koonin [steven.koonin@gmail.com]  
**CC:** Roy Spencer [roywspencer@hotmail.com]; Ross McKittrick [ross.mckittrick@gmail.com]; John Christy [climateman60@gmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]  
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The global greening chapter can be short and sweet like ocean alkalinity, with ag specific details in Ch10

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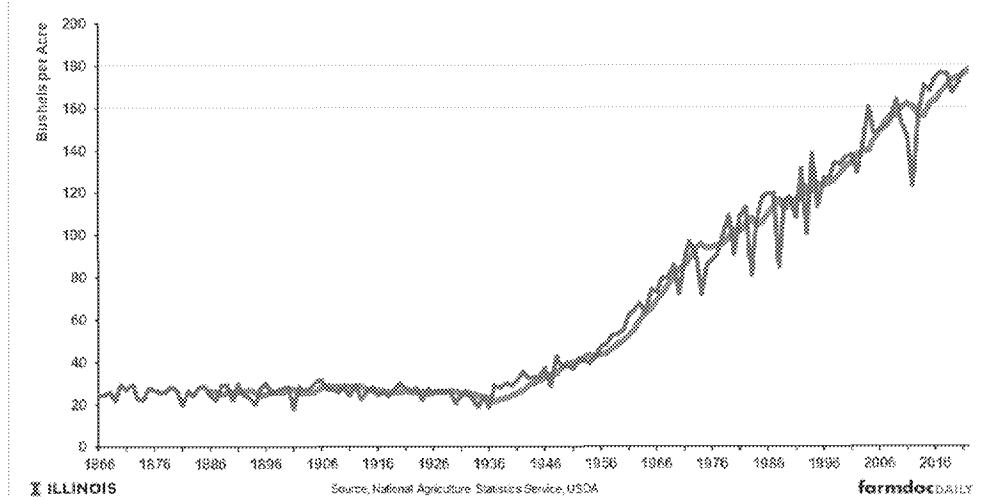
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**From:** Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)>  
**Sent:** Tuesday, May 6, 2025 10:10 AM  
**To:** 'Judith Curry' <[curry.judith@gmail.com](mailto:curry.judith@gmail.com)>  
**Cc:** 'Ross McKittrick' <[ross.mckittrick@gmail.com](mailto:ross.mckittrick@gmail.com)>; 'John Christy' <[climateman60@gmail.com](mailto:climateman60@gmail.com)>; 'Roy W. Spencer' <[roywspencer@hotmail.com](mailto:roywspencer@hotmail.com)>; 'Travis Fisher' <[travis.scott.fisher@gmail.com](mailto:travis.scott.fisher@gmail.com)>  
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Figure 1. Actual and Trend Yields for Corn, 1886 to 2022



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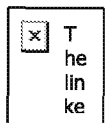
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**From:** Roy Spencer <roywspencer@hotmail.com>  
**Sent:** Tuesday, May 6, 2025 12:14 PM  
**To:** Steven Koonin; 'Judith Curry'  
**Cc:** 'Ross McKitrick'; 'John Christy'; 'Travis Fisher'  
**Subject:** Re: My suggested edits of Chapter 10

Agreed.  
-Roy

---

**From:** Steven Koonin <steven.koonin@gmail.com>  
**Sent:** Tuesday, May 6, 2025 10:54 AM  
**To:** 'Judith Curry' <curry.judith@gmail.com>  
**Cc:** 'Roy Spencer' <roywspencer@hotmail.com>; 'Ross McKitrick' <ross.mckitrick@gmail.com>; 'John Christy' <climateman60@gmail.com>; 'Travis Fisher' <travis.scott.fisher@gmail.com>  
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**To:** Steven Koonin <steven.koonin@gmail.com>  
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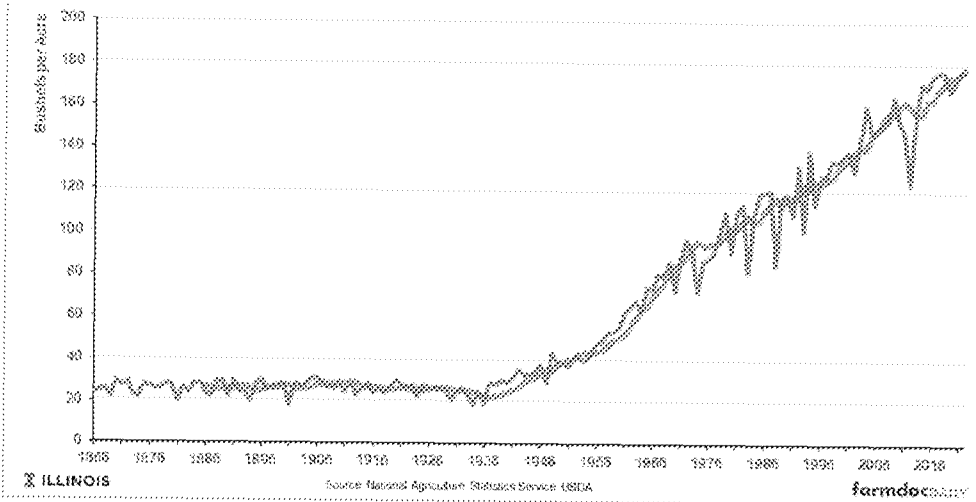
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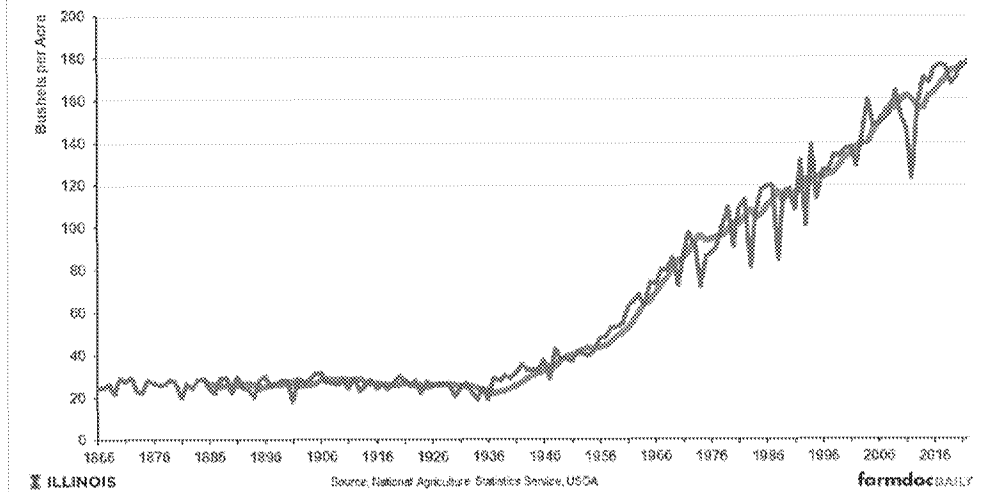
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**Cc:** Ross McKittrick <[ross.mckittrick@gmail.com](mailto:ross.mckittrick@gmail.com)>; John Christy <[climateman60@gmail.com](mailto:climateman60@gmail.com)>; Roy W. Spencer <[roywspencer@hotmail.com](mailto:roywspencer@hotmail.com)>; Travis Fisher <[travis.scott.fisher@gmail.com](mailto:travis.scott.fisher@gmail.com)>

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See attached.

SEK

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**Sent:** Tuesday, May 6, 2025 11:52 AM  
**To:** Steven Koonin  
**Cc:** Roy Spencer; Ross McKittrick; John Christy; Travis Fisher  
**Subject:** Re: My suggested edits of Chapter 10

For ch 10, i prefer to move the crop material from ch 2 to ch 10, and then talk about the confounding factors in attributing yield increases

On Tue, May 6, 2025 at 8:49 AM Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)> wrote:

Right. And then there are papers claiming that the trend isn't as large as it might have been because of "climate change". But the claimed decrements are small and, more importantly, there's no way to prove that counterfactual.

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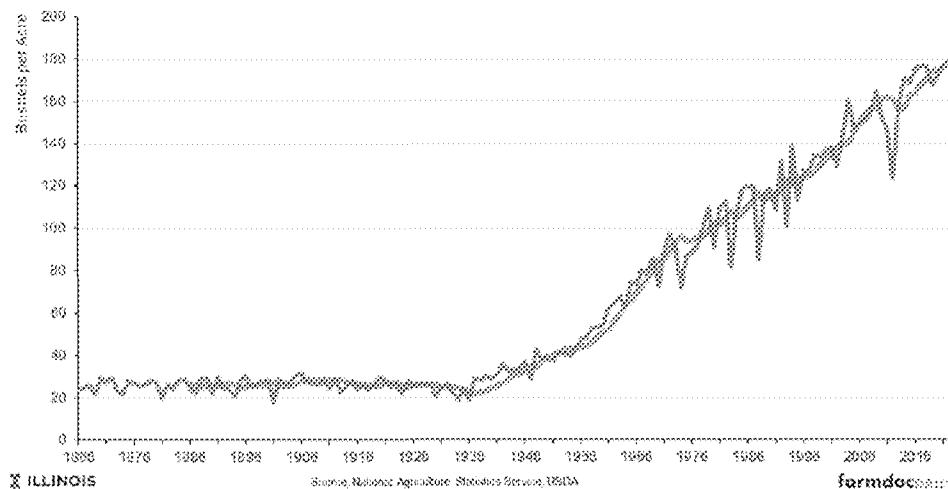
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Figure 1. Actual and Trend Yields for Corn, 1886 to 2022



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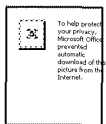
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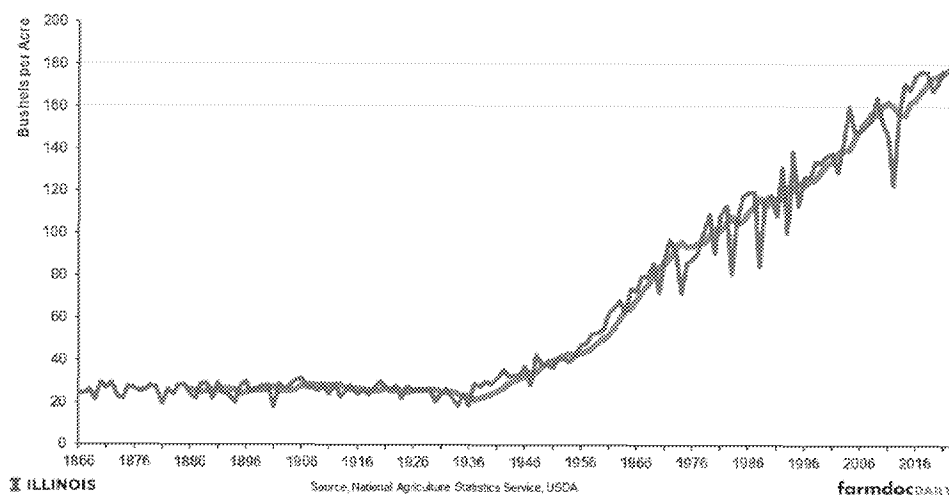
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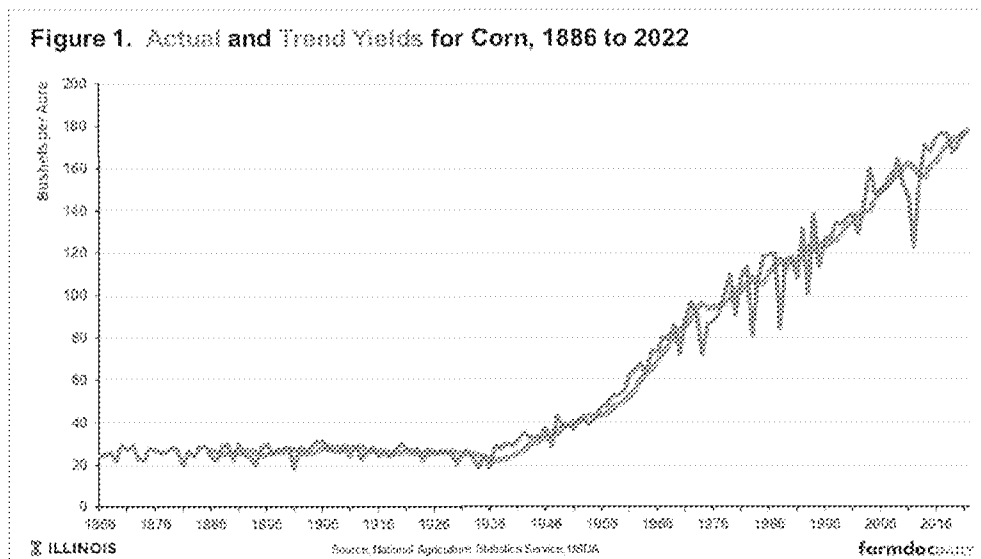
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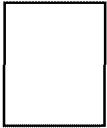
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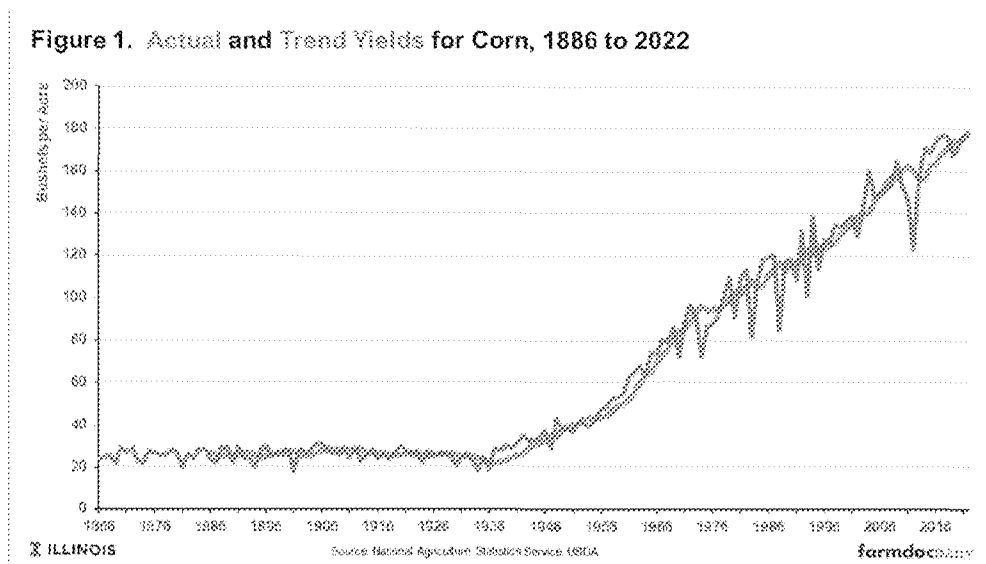
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**Sent:** Tuesday, May 6, 2025 11:11 AM  
**To:** 'Judith Curry'  
**Cc:** 'Ross McKittrick'; 'John Christy'; 'Roy W. Spencer'; 'Travis Fisher'  
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**Attachments:** ~WRD3589.jpg; image001.png

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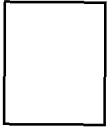
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**Attachments:** 10 Climate and Agriculture.May6[SEK] CURRY.docx

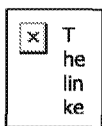
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## 10. Climate change and US agriculture

### 10.1 Ricardian analysis **CHANGE THE SECTION TITLE TO SOMETHING PEOPLE WILL UNDERSTAND WITHOUT DEFINING THE WORD RICARDIAN**

Scientists have long known about the beneficial effect of CO<sub>2</sub> on plant growth and have studied it extensively. Thousands of experiments in laboratories and outdoor field settings (CO2Science.org, undated) have confirmed beneficial effects for food plants and crops of all kinds from higher CO<sub>2</sub> levels.

Evidence that CO<sub>2</sub>-induced warming will be neutral or beneficial for agriculture, particularly in the US, goes back decades. Mendelsohn et al. (1994) examined the effects of historical climatic variations on agricultural land values and concluded “our projections suggest that global warming may be slightly beneficial to American agriculture.” Mendelsohn et al. (2000) provided a global assessment of the impacts of 2°C warming by 2060 (equivalent to 3.3 °C warming per century). They concluded that 2°C warming “will result in net market benefits for most OECD countries”. Tol (2002) published estimates of the global impact on agriculture of a 2.5 degree C warming. Assuming farmers adapt to the changes, he expected every region to end up better off.

**DEFINE LAND VALUE ARE YOU JUST TALKING ABOUT AGRICULTURE OR SOMETHING ELSE** There have been criticisms of the methodology used by Mendelsohn et al. (1994) to associate land value changes with climate change. It potentially omits other important determinants of land value that change over time **SUCH AS WHAT**, leading some authors to argue that the benefits of warming would be much smaller or even negative. Bareille and Chakir (2023) addressed the criticisms by assembling a large data base on farm sale prices in France for properties that sold twice between 1996 and 2019. By comparing the change in land value on the same farm to local climatic and economic changes they were able to remove the confounding influence of fixed site-specific characteristics and isolate the contribution of climate variables. Those authors concluded that, taking adaptation into account, a warming climate would yield positive benefits for French agriculture that were between two and 20 times larger than had previously been estimated. On average, with full adaptation, climate changes anticipated under the medium RCP4.5 scenario could double the value of French farmland by 2100. They also noted that application of earlier methods to the same data suggests climate change would harm French agriculture.

**THE PREVIOUS PARAGRAPHS ARE CONFUSING. I WOULD JUST TALK ABOUT AGRICULTURE AND NOT LAND VALUE, UNLESS YOU DEFINE NON-AG VALUES**

### 10.2 Field studies

As discussed in Chapter 2 **I PREFER TO SEE THIS MATERIAL IN CHAPTER 10 RATHER THAN IN CHAPTER 2**, scientists have used so-called Free Air CO<sub>2</sub> Enrichment, or FACE, experiments to measure how plants in outdoor settings respond to local increases in the concentration of carbon dioxide. In a 2021 study that reviewed 160 FACE experiments conducted over 20 years, Hu *et al.* (2021) concluded that elevated CO<sub>2</sub> levels had boosted rice growth on average by 16 percent. Furthermore, when they looked at hybrid varieties particularly suited to the higher CO<sub>2</sub> levels, growth increased by nearly 25 percent.

Wheat also benefits from CO<sub>2</sub>-induced climate change. The website CO2Science.org ([http://www.co2science.org/data/plant\\_growth/photo/t/triticuma.php](http://www.co2science.org/data/plant_growth/photo/t/triticuma.php)) reports on 92 published experiments between 1983 and 2020 exposing wheat to enriched CO<sub>2</sub> levels. Converted to a +300 parts per million common scale, the average growth boost was 67.6 percent.



A 2021 report from the US National Bureau of Economic Research (Taylor and Schlenker 2021) used satellite-measured observations of outdoor CO<sub>2</sub> levels across the United States, matched to county-level agricultural output data and other economic variables. After controlling for the effects of weather, pollution and technology the authors concluded that CO<sub>2</sub> emissions had boosted US crop production since 1940 by 50 to 80 percent, attributing much larger gains than had previously been estimated using FACE experiments. They found that every ppm of increase in CO<sub>2</sub> concentration boosts corn yields by 0.5 percent, soybeans by 0.6 percent, and wheat by 0.8 percent.

Beyond growth benefits, extra CO<sub>2</sub> boosts plant resilience to heat. Derying et al. (2016) surveyed all available evidence regarding how wheat, maize, rice and soybean will grow under a combination of climate warming and rising CO<sub>2</sub> levels. ~~DUPLICATIVE OF CH 2, I PREFER THIS MATERIAL IN CH 10~~ They concluded that warming would, eventually, have a negative effect on plant growth but it would be fully compensated by the extra CO<sub>2</sub> for wheat and soybean, and almost fully for rice and maize. And as discussed in Chapter 2, plants use water more efficiently when there is more CO<sub>2</sub> in the air.

Adaption plays a key role in exploiting gains from climate change for US crops. Butler et al. (2018) examined US maize production since 1981 and found that weather changes had been a net benefit. They also found that “current farmer cropping schedules are more beneficial in the climate of the last decade than they would have been in earlier decades” and adaptive responses to warming had added 13 kg per hectare to maize production. They estimated that weather trends since 1981 had boosted US maize production by 28% since 1981.

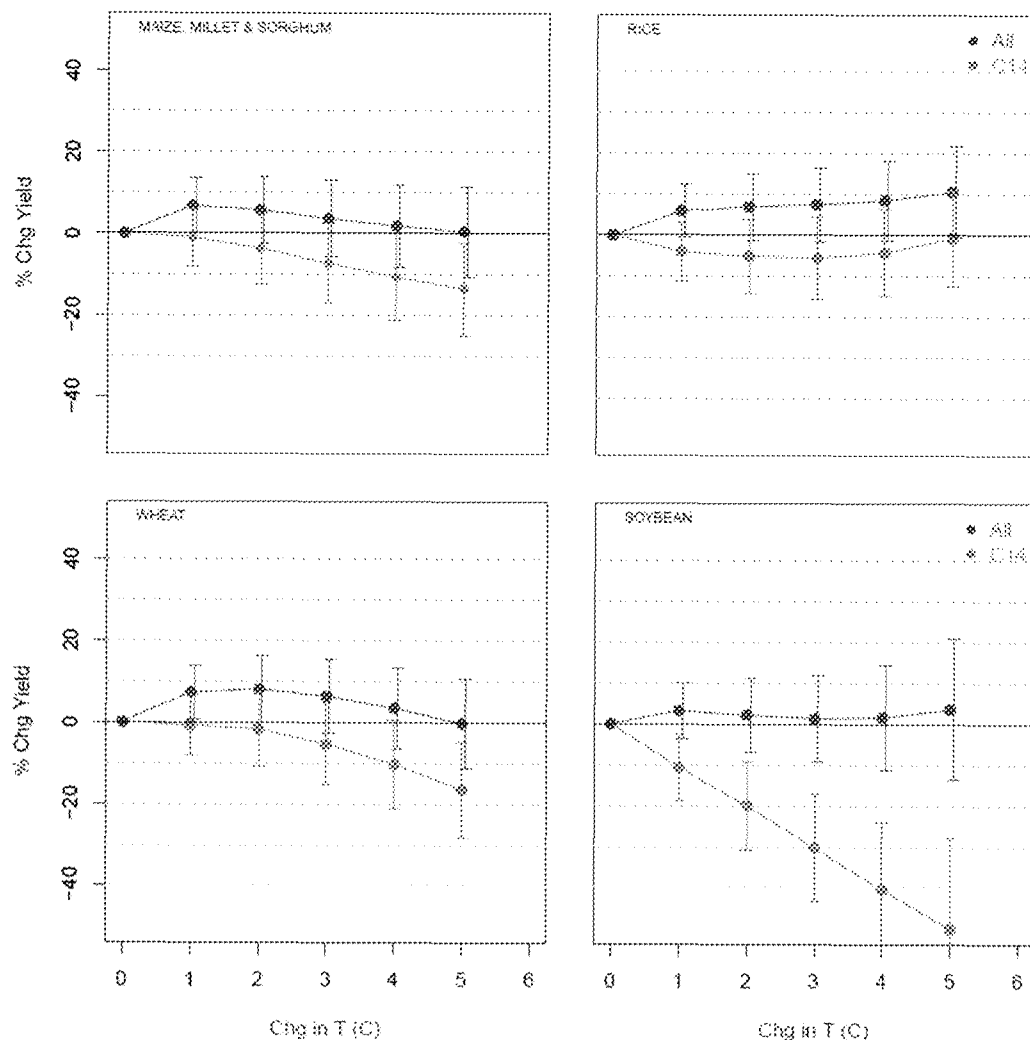
### 10.3 Crop modeling meta-analyses

Notwithstanding the abundant evidence for the direct benefits of CO<sub>2</sub> and of CO<sub>2</sub>-induced warming on crop growth, in 2023 the US Environmental Protection Agency (EPA 2023) boosted its estimate of the Social Cost of Carbon (SCC) about five-fold based in large part on a very pessimistic 2017 estimate of global agricultural damages from climate warming. One of the two damage models used by the EPA (Moore et al., 2017) attributed nearly half of the 2030 SCC to projected global agricultural damages based on a ~~The EPA used two damage models and in one of them, of the new 2030-SCC value nearly half was attributed to projected global agricultural damages estimated in Moore et al. (2017, denoted M17), which was in turn a reanalysis of a database first presented in Challinor et al. (2014, denoted C14).~~ The Challinor data base was a meta-analysis of crop model studies simulating yield changes for agricultural crops under various climate warming scenarios. ~~M17~~ Moore et al. projected declining global crop yields for all crop types in all regions due to warming.

McKittrick (2025) re-examined the Challinor database and found that, while it claimed to cover 1,722 studies, only half the entries ( $N=862$ ) had complete records, so that the sample available for regression analysis was much smaller than both studies indicated. McKittrick noted that the variable most commonly missing was the change in ambient CO<sub>2</sub> and found that in many cases these could be recovered from the underlying studies or the original climate scenario tables. He thereby increased the usable sample size by 40 percent. The crop yield projections incorporating the newly available data changed considerably. As shown in Figure 10.1, whereas the partial data set implied warming would decrease yield (blue lines), the complete data set implied constant or increase global yields, even out to 5°C warming (green lines).

In summary, there is abundant evidence going back decades that rising CO<sub>2</sub> levels benefit plants including agricultural crops, and that CO<sub>2</sub>-induced warming will be a net benefit to US agriculture. The warming since 1981, in combination with adaptive behaviour by farmers, has been beneficial on

its own for maize. The increased ambient CO<sub>2</sub> has also boosted productivity of all major US crop types. Various attempts to argue that CO<sub>2</sub>-induced warming will harm agriculture do not hold up under scrutiny.



**Figure 10.1** Crop yields under CO<sub>2</sub>-induced climate warming. Blue: as published in Moore et al. (2017). Green: after including omitted data. Source: McKittrick (2025).

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As discussed in Chapter 2, scientists have used so-called Free Air CO<sub>2</sub> Enrichment, or FACE, experiments to measure how plants in outdoor settings respond to local increases in the concentration of carbon dioxide. In a 2021 study that reviewed 160 FACE experiments conducted over 20 years, Hu *et al.* (2021) concluded that elevated CO<sub>2</sub> levels had boosted rice growth on average by 16 percent. Furthermore, when they looked at hybrid varieties particularly suited to the higher CO<sub>2</sub> levels, growth increased by nearly 25 percent.

Wheat also benefits from CO<sub>2</sub>-induced climate change. The website CO2Science.org ([http://www.co2science.org/data/plant\\_growth/photo/t/triticuma.php](http://www.co2science.org/data/plant_growth/photo/t/triticuma.php)) reports on 92 published experiments between 1983 and 2020 exposing wheat to enriched CO<sub>2</sub> levels. Converted to a +300 parts per million common scale, the average growth boost was 67.6 percent.

A 2021 report from the US National Bureau of Economic Research (Taylor and Schlenker 2021) used satellite-measured observations of outdoor CO<sub>2</sub> levels across the United States, matched to county-level agricultural output data and other economic variables. After controlling for the effects of weather, pollution and technology the authors concluded that CO<sub>2</sub> emissions had boosted US crop production since 1940 by 50 to 80 percent, attributing much larger gains than had previously

been estimated using FACE experiments. They found that every ppm increase in CO<sub>2</sub> concentration boosts corn yields by 0.5 percent, soybeans by 0.6 percent and wheat by 0.8 percent.

Beyond growth benefits, extra CO<sub>2</sub> boosts plant resilience to heat. Derying et al. (2016) surveyed all available evidence regarding how wheat, maize, rice and soybean will grow under a combination of climate warming and rising CO<sub>2</sub> levels. They concluded that warming would, eventually, have a negative effect on plant growth but it would be fully compensated by the extra CO<sub>2</sub> for wheat and soybean, and almost fully for rice and maize. And as discussed in Chapter 2, plants use water more efficiently when there is more CO<sub>2</sub> in the air.

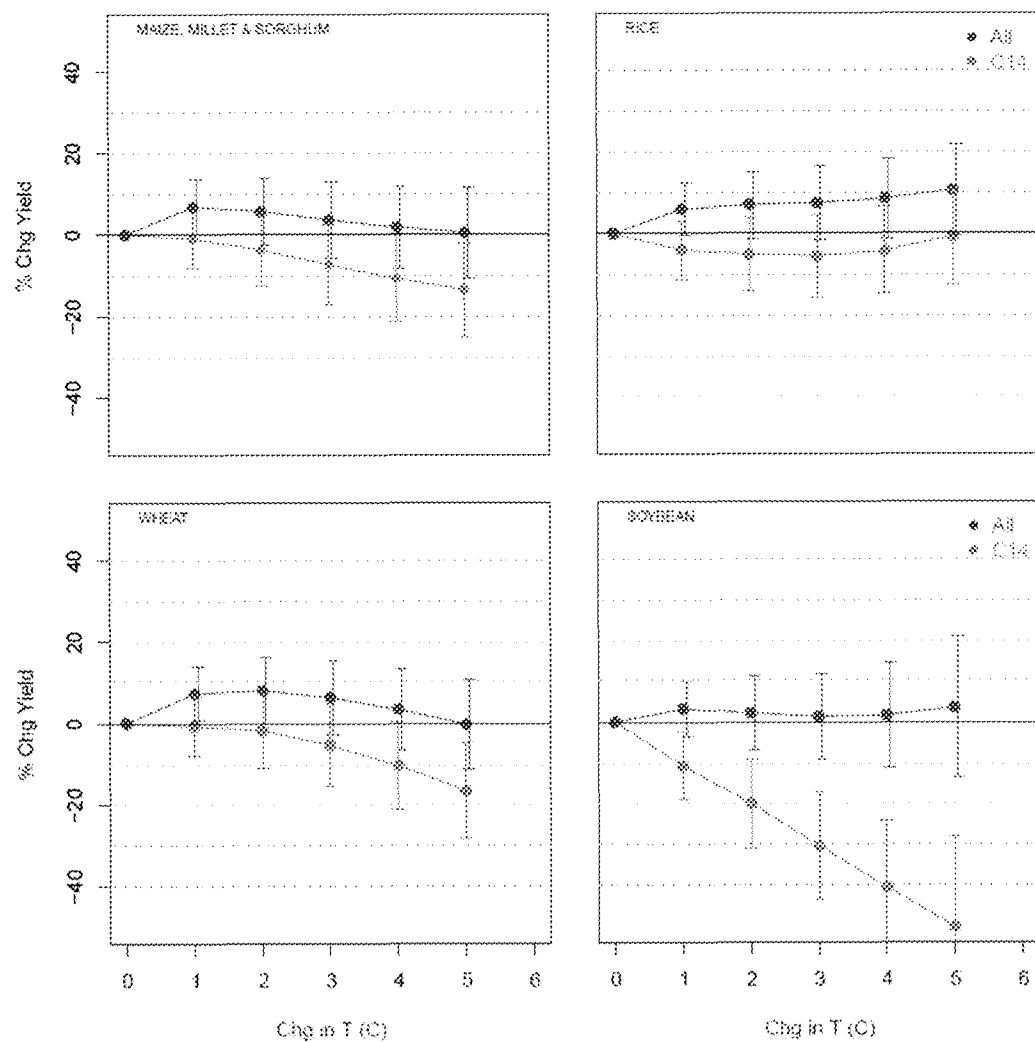
Adaption plays a key role in exploiting gains from climate change for US crops. Butler et al. (2018) examined US maize production since 1981 and found that weather changes had been a net benefit. They also found that “current farmer cropping schedules are more beneficial in the climate of the last decade than they would have been in earlier decades” and adaptive responses to warming had added 13 kg per hectare to maize production. They estimated that weather trends since 1981 had boosted US maize production by 28% since 1981.

### **10.3 Crop modeling meta-analyses**

Notwithstanding the abundant evidence for the direct benefits of CO<sub>2</sub> and of CO<sub>2</sub>-induced warming on crop growth, in 2023 the US Environmental Protection Agency (EPA 2023) boosted its estimate of the Social Cost of Carbon (SCC) about five-fold based in large part on a very pessimistic 2017 estimate of global agricultural damages from climate warming. The EPA used two damage models and in one of them, of the new 2030 SCC value nearly half was attributed to projected global agricultural damages estimated in Moore et al. (2017, denoted M17), which was in turn a reanalysis of a database first presented in Challinor et al. (2014, denoted C14). The Challinor data base was a meta-analysis of crop model studies simulating yield changes for agricultural crops under various climate warming scenarios. M17 projected declining global crop yields for all crop types in all regions due to warming.

McKittrick (2025) re-examined the C14 database and found that, while it claimed to cover 1,722 studies, only half the entries ( $N=862$ ) had complete records, so that the sample available for regression analysis was much smaller than both studies indicated. McKittrick noted that the variable most commonly missing was the change in ambient CO<sub>2</sub> and found that in many cases these could be recovered from the underlying studies or the original climate scenario tables. He thereby increased the usable sample size by 40 percent. The crop yield projections incorporating the newly available data changed considerably. As shown in Figure 10.1, whereas the partial data set implied warming would decrease yield (blue lines) the complete data set implied constant or increase global yields, even out to 5°C warming (green lines).

In summary there is abundant evidence going back decades that rising CO<sub>2</sub> levels benefit plants including agricultural crops, and that CO<sub>2</sub>-induced warming will be a net benefit to US agriculture. The warming since 1981, in combination with adaptive behaviour by farmers, has been beneficial on its own for maize. The increased ambient CO<sub>2</sub> has also boosted productivity of all major US crop types. Various attempts to argue that CO<sub>2</sub>-induced warming will harm agriculture do not hold up under scrutiny.



**Figure 10.1** Crop yields under CO<sub>2</sub>-induced climate warming. Blue: as published in Moore et al. (2017). Green: after including omitted data. Source: McKittrick (2025).

---

**From:** Travis Fisher <travis.scott.fisher@gmail.com>  
**Sent:** Tuesday, May 13, 2025 8:06 AM  
**To:** Roy Spencer  
**Cc:** Steven Koonin; Ross McKittrick; Judith Curry; John Christy  
**Subject:** Re: The week upcoming

Dropbox: [https://www.dropbox.com/scl/fo/wahx6lpwzu33m5vyrrri8x/AKXx1DAsKO1R5EuV1SQco-s/00.Report%20Draft?dl=0&e=2&rlkey=11z3qj9v46e1t5f4ywwxq7p8c&subfolder\\_nav\\_tracking=1](https://www.dropbox.com/scl/fo/wahx6lpwzu33m5vyrrri8x/AKXx1DAsKO1R5EuV1SQco-s/00.Report%20Draft?dl=0&e=2&rlkey=11z3qj9v46e1t5f4ywwxq7p8c&subfolder_nav_tracking=1)

It looks like tomorrow (Wednesday) afternoon is the winner. I'll send a link later today.

On Tue, May 13, 2025 at 5:02 AM Roy Spencer <roywspencer@hotmail.com> wrote:

Can someone send me the dropbox link? I only have my phone on travel and I can't find it anywhere... not even Ross' original email. - Roy

Sent from my Verizon, Samsung Galaxy smartphone

----- Original message -----

From: Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)>  
Date: 5/13/25 4:37 AM (GMT-05:00)  
To: Travis Fisher <[travis.scott.fisher@gmail.com](mailto:travis.scott.fisher@gmail.com)>  
Cc: Ross McKittrick <[ross.mckittrick@gmail.com](mailto:ross.mckittrick@gmail.com)>, Judith Curry <[curry.judith@gmail.com](mailto:curry.judith@gmail.com)>, "Roy W. Spencer" <[roywspencer@hotmail.com](mailto:roywspencer@hotmail.com)>, John Christy <[climateman60@gmail.com](mailto:climateman60@gmail.com)>  
Subject: Re: The week upcoming

I'm free anytime Wednesday (I'll be at Stanford).

Friday won't work as I'll be flying back East (to EWR, I hope)

Steven Koonin

On May 12, 2025, at 20:20, Travis Fisher <[travis.scott.fisher@gmail.com](mailto:travis.scott.fisher@gmail.com)> wrote:

This is already a very impressive document. Kudos, and I can't wait to see where we are in another 9-10 days!

I'm happy to set up a Google Meet or Zoom or whatever type of video conference people prefer. This Wednesday afternoon or anytime Friday would work well for me. What time works best for the group?

And do you all mind if I include Josh Loucks, my former RA at Cato (now at DOE)? He'll be doing a lot of the document production work.

On Sat, May 10, 2025 at 11:11 AM Ross McKittrick <[ross.mckittrick@gmail.com](mailto:ross.mckittrick@gmail.com)> wrote:  
I just had a read through of the chapters and for fun put them into a single word doc to see what we've got in terms of length. It's about 150 pages, so it looks like we'll tick both the quality and quantity boxes. I attached the draft for your interest but I'm not putting it into Dropbox bc we've still got work to do on each chapter.

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Also in some chapters people have inserted figures without captions and/or sources. Please provide them.

Roy and I have to travel to DC Tuesday but I'd like to suggest we arrange a zoom meeting later in the week to talk through the remaining issues chapter by chapter. I propose Wednesday afternoon but I can make other times available. That gives everyone time to go through what we've now got and then 2 weeks to finish. There are substantial document production steps needed, including formatting, fixing the references and compiling the complete list, getting figure reproduction permissions, etc.

Ross



---

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**Sent:** Tuesday, May 13, 2025 5:02 AM  
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**Cc:** Ross McKitrick; Judith Curry; John Christy  
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Ross

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**Sent:** 5/10/2025 3:11:30 PM  
**To:** Judith Curry [curry.judith@gmail.com]; Roy W. Spencer [roywspencer@hotmail.com]; John Christy [climatemanager60@gmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]; Steven Koonin [steven.koonin@googlemail.com]  
**Subject:** The week upcoming  
**Attachments:** 00.May10.Fulldraft.docx

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Ross

United States Department of Energy

Climate Science, Greenhouse Gases  
and the Management of US Weather Risks

Report of the Climate Science Advisory Group

May 28, 2025

Climate Science, Greenhouse Gases  
and the Management of US Weather Risks

Report of the Climate Science Advisory Group

John Christy, Ph.D.

Judith Curry, Ph.D.

Steven Koonin, Ph.D.

Ross McKittrick, Ph.D.

Roy Spencer, Ph.D.

## Table of Contents

|                                                                                  |           |
|----------------------------------------------------------------------------------|-----------|
| <b>FOREWORD: SECRETARY CHRIS WRIGHT .....</b>                                    | <b>5</b>  |
| <b>FOREWORD: CSAG .....</b>                                                      | <b>6</b>  |
| <b>PART I: DIRECT HUMAN INFLUENCE ON ECOSYSTEMS AND THE CLIMATE .....</b>        | <b>7</b>  |
| <b>1. CARBON DIOXIDE AS DISTINCT FROM CRITERIA AIR CONTAMINANTS .....</b>        | <b>8</b>  |
| <b>2. CO<sub>2</sub> FERTILIZATION AND GLOBAL GREENING .....</b>                 | <b>9</b>  |
| 2.1. CO <sub>2</sub> AND GLOBAL GREENING .....                                   | 9         |
| 2.2. PHOTOSYNTHESIS AND CO <sub>2</sub> LEVELS .....                             | 10        |
| 2.3. RISING CO <sub>2</sub> AND CROP WATER USE EFFICIENCY .....                  | 12        |
| 2.4. CONCEALMENT OF CO <sub>2</sub> FERTILIZATION BENEFITS IN IPCC REPORTS ..... | 13        |
| <b>3. INCREASING CO<sub>2</sub> AND THE ALKALINE OCEANS .....</b>                | <b>15</b> |
| <b>4. HUMAN INFLUENCES ON THE CLIMATE.....</b>                                   | <b>17</b> |
| 4.1. COMPONENTS OF RADIATIVE FORCING AND THEIR HISTORY .....                     | 17        |
| 4.2. FUTURE EMISSION SCENARIOS AND THE CARBON CYCLE.....                         | 20        |
| 4.3. AEROSOLS AND THE UNCERTAINTIES ASSOCIATED WITH THEM .....                   | 24        |
| <b>PART II: CLIMATE RESPONSE TO GREENHOUSE GAS EMISSIONS.....</b>                | <b>28</b> |
| <b>5. CLIMATE SENSITIVITY TO CO<sub>2</sub> FORCING .....</b>                    | <b>29</b> |
| 5.1. INTRODUCTION .....                                                          | 29        |
| 5.2. MODEL-BASED METHODS OF COMPUTING CLIMATE SENSITIVITY TO GHGs.....           | 29        |
| 5.3. DATA-DRIVEN METHODS OF COMPUTING CLIMATE SENSITIVITY TO GHGs .....          | 30        |
| 5.4. TRANSIENT CLIMATE RESPONSE.....                                             | 32        |
| 5.5. SUMMARY .....                                                               | 33        |
| <b>6. MODELS VERSUS OBSERVATIONS IN THE RECENT PAST .....</b>                    | <b>36</b> |
| 6.1. INTRODUCTION .....                                                          | 36        |
| 6.2. SURFACE WARMING .....                                                       | 36        |
| 6.3. TROPOSPHERIC WARMING .....                                                  | 38        |
| 6.4. VERTICAL PROFILE MISMATCH AND EXCESS AMPLIFICATION .....                    | 42        |
| 6.5. STRATOSPHERIC COOLING .....                                                 | 46        |
| 6.6. WATER VAPOUR TRENDS .....                                                   | 46        |
| 6.7. SNOW COVER .....                                                            | 47        |
| 6.8. US CORN BELT .....                                                          | 48        |
| <b>7. UNCERTAINTIES IN CLIMATE CHANGE ATTRIBUTION.....</b>                       | <b>51</b> |
| 7.1. INTRODUCTION .....                                                          | 51        |
| 7.2. NATURAL CLIMATE VARIABILITY .....                                           | 53        |
| 7.3. OPTIMAL FINGERPRINTING .....                                                | 56        |
| 7.4. TIME SERIES METHODS.....                                                    | 57        |
| 7.5. EXTREME EVENT ATTRIBUTION (EEA).....                                        | 58        |
| 7.6. CASE STUDY – 2021 WESTERN NORTH AMERICA HEAT WAVE .....                     | 60        |
| 7.7. SUMMARY .....                                                               | 61        |
| <b>8. EXTREME WEATHER IN THE US AND ELSEWHERE.....</b>                           | <b>68</b> |

|                                                          |                                                                                 |            |
|----------------------------------------------------------|---------------------------------------------------------------------------------|------------|
| 8.1.                                                     | INTRODUCTION .....                                                              | 68         |
| 8.2.                                                     | REVIEW OF IPCC AND NCA FINDINGS ON EXTREME WEATHER .....                        | 69         |
| 8.3.                                                     | EXTREME WEATHER TRENDS AT GLOBAL AND CONTINENTAL SCALE .....                    | 84         |
| 8.4.                                                     | TEMPERATURE AND PRECIPITATION EXTREMES IN THE CONTIGUOUS US (CONUS) .....       | 90         |
| <b>9.</b>                                                | <b>CHANGES IN SEA LEVEL.....</b>                                                | <b>105</b> |
| 9.1.                                                     | U.S. COASTAL SEA LEVEL RISE .....                                               | 105        |
| 9.2.                                                     | SEA LEVEL RISE PROJECTIONS .....                                                | 109        |
| 9.3.                                                     | SUMMARY .....                                                                   | 110        |
| <b>PART III: IMPACTS ON ECOSYSTEMS AND SOCIETY .....</b> |                                                                                 | <b>111</b> |
| <b>10.</b>                                               | <b>CLIMATE CHANGE AND US AGRICULTURE.....</b>                                   | <b>112</b> |
| 10.1.                                                    | ECONOMETRIC ANALYSES.....                                                       | 112        |
| 10.2.                                                    | FIELD STUDIES OF CO <sub>2</sub> ENRICHMENT .....                               | 113        |
| 10.3.                                                    | CROP MODELING META-ANALYSES.....                                                | 115        |
| <b>11.</b>                                               | <b>MANAGING RISKS OF EXTREME WEATHER .....</b>                                  | <b>118</b> |
| 11.1.                                                    | SOCIOECONOMIC CONTEXT .....                                                     | 118        |
| 11.2.                                                    | DATA CHALLENGES .....                                                           | 118        |
| <b>12.</b>                                               | <b>MORTALITY FROM TEMPERATURE EXTREMES .....</b>                                | <b>120</b> |
| 12.1.                                                    | HEAT AND COLD RISKS.....                                                        | 120        |
| 12.2.                                                    | THE IMPORTANCE OF ADAPTATION.....                                               | 122        |
| 12.3.                                                    | MORTALITY RISKS AND ENERGY COSTS .....                                          | 122        |
| <b>13.</b>                                               | <b>CLIMATE CHANGE, THE ECONOMY AND THE SOCIAL COST OF CARBON.....</b>           | <b>124</b> |
| 13.1.                                                    | CLIMATE CHANGE AND ECONOMIC GROWTH .....                                        | 124        |
| 13.2.                                                    | MODELS OF THE SOCIAL COST OF CARBON .....                                       | 128        |
| 13.3.                                                    | SUMMARY .....                                                                   | 132        |
| <b>14.</b>                                               | <b>U.S. VEHICLE-BASED CO<sub>2</sub> EMISSIONS AND THE GLOBAL CLIMATE .....</b> | <b>135</b> |
| <b>15.</b>                                               | <b>REFERENCES .....</b>                                                         | <b>136</b> |
| <b>16.</b>                                               | <b>GLOSSARY OF TERMS .....</b>                                                  | <b>143</b> |
| <b>17.</b>                                               | <b>ABOUT THE AUTHORS .....</b>                                                  | <b>146</b> |



## Foreword: Secretary Chris Wright

## Foreword: CSAG

This document originated in late March 2025 when Secretary Wright assembled an independent team to write a report on issues in climate science relevant for energy policymaking, with particular focus on the question of whether carbon dioxide emissions endanger the US public. The team agreed to undertake the work on the condition that there would be no editorial oversight by the Secretary, the Department of Energy, or any other government personnel. This condition has been honored throughout the process and the writing team has worked with full independence.

The team began working in early April with a deadline of May 28. The short timeline and the technical nature of the material meant that we could not comprehensively review all topics. While the report is intended to be accessible for non-experts, we have omitted some introductory or explanatory material that can easily be accessed elsewhere. Nor have we attempted to survey entire literatures related to the topics covered. The scientific and technical material herein only samples vast literature on climate change but is, we believe, more than sufficient to establish our conclusions.

*The team writing this report was not involved in, nor briefed on, any Administration plans or processes related to a potential challenge to the 2009 EPA CO<sub>2</sub> Endangerment Finding.* We were asked, however, to include some information related to the role of US motor vehicles in global climate change, since that is an issue of relevance to the Department of Energy.

The writing team is grateful to Secretary Wright for the opportunity to prepare this report and for his support for independent scientific inquiry.

## Part I: Direct Human Influence on Ecosystems and the Climate

# 1. Carbon dioxide as distinct from criteria air contaminants

This report is chiefly concerned with carbon dioxide (CO<sub>2</sub>) emissions from fossil fuel use. Although it has become common to refer to CO<sub>2</sub> as “pollution” this is a misnomer. In the framework of United States clean air policy there are six types of so-called Criteria Air Contaminants (EPA, undated): particulate matter, ground-level ozone, Sulfur Dioxide, Nitrogen Dioxide, Lead and carbon monoxide (CO). Air contaminants are subject to regulatory control because they cause local problems depending on concentrations that include nuisances (odor, visibility problems), damage to plants and, at high enough exposure levels, toxicological effects in humans.

CO<sub>2</sub> has not historically been viewed as an air pollutant in the US or elsewhere because it is odorless, does not affect visibility and has no toxicological effects at ambient levels. It is a naturally-occurring part of the atmosphere and a key component of human and plant respiration. CO<sub>2</sub> is essential for plant photosynthesis and higher levels are generally considered beneficial for vegetation, as will be discussed in this report.

Ambient outdoor air contains about 420 parts per million (ppm) CO<sub>2</sub>. The US Occupational Safety and Health Administration issues guidelines for indoor workplaces in which elevated CO<sub>2</sub> may be encountered, such as where dry ice is used. The Permissible Exposure Limit is 5,000 ppm over 8 hours (OSHA 2024). Allen et al. (2015) reported evidence of diminished performance on some cognitive tasks among workers in office cubicles when exposed to CO<sub>2</sub> levels above 1,000-1,500 ppm.

The main concern about CO<sub>2</sub> is its potential effects on the global climate. This is a very complex question which will occupy much of this report. We will begin in the next section by looking at the role of CO<sub>2</sub> in promoting global greening and agricultural productivity growth, then we will examine the effect of CO<sub>2</sub> on ocean alkalinity. We then turn to CO<sub>2</sub>'s role as a so-called greenhouse gas (GHG), beginning with a brief description of radiative forcing, the carbon cycle and the role of aerosols. Part II of this report discusses in detail the topic of the climatic response to GHGs. Part III discusses some aspects of the impacts of climate change on ecosystems and society.

US Environmental Protection Agency (Undated) Criteria Air Pollutants. <https://www.epa.gov/criteria-air-pollutants> accessed April 29 2025.

US Occupational Health and Safety Administration (2024) “OSHA Occupational Chemical Database: Carbon Dioxide” <https://www.osha.gov/chemicaldata/183>

Allen, Joseph G, Piers MacNaughton, Usha Satish, Suresh Santanam, Jose Vallarino and John D.S. Spengler (2015) Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation, and Volatile Organic Compound Exposures in Office Workers: A Controlled Exposure Study of Green and Conventional

## 2. CO<sub>2</sub> fertilization and global greening

### 2.1. CO<sub>2</sub> and global greening

“Greening” refers to an increase in the total amount of the Earth’s surface covered in plants. The main measure of greening is “Leaf Area Index” or LAI as measured by satellite. Many studies over the past decade have confirmed a global greening pattern (rising LAI) attributable to rising CO<sub>2</sub> levels. Zhu et al. (2016) was one of the first studies to report that global greening was detectable from space using satellite sensors. On data spanning 1982 to 2011 they detected greening over 25-50% of the Earth versus browning over only 4%, and they attributed 70% of the greening to rising CO<sub>2</sub> levels (see Figure 2.3).

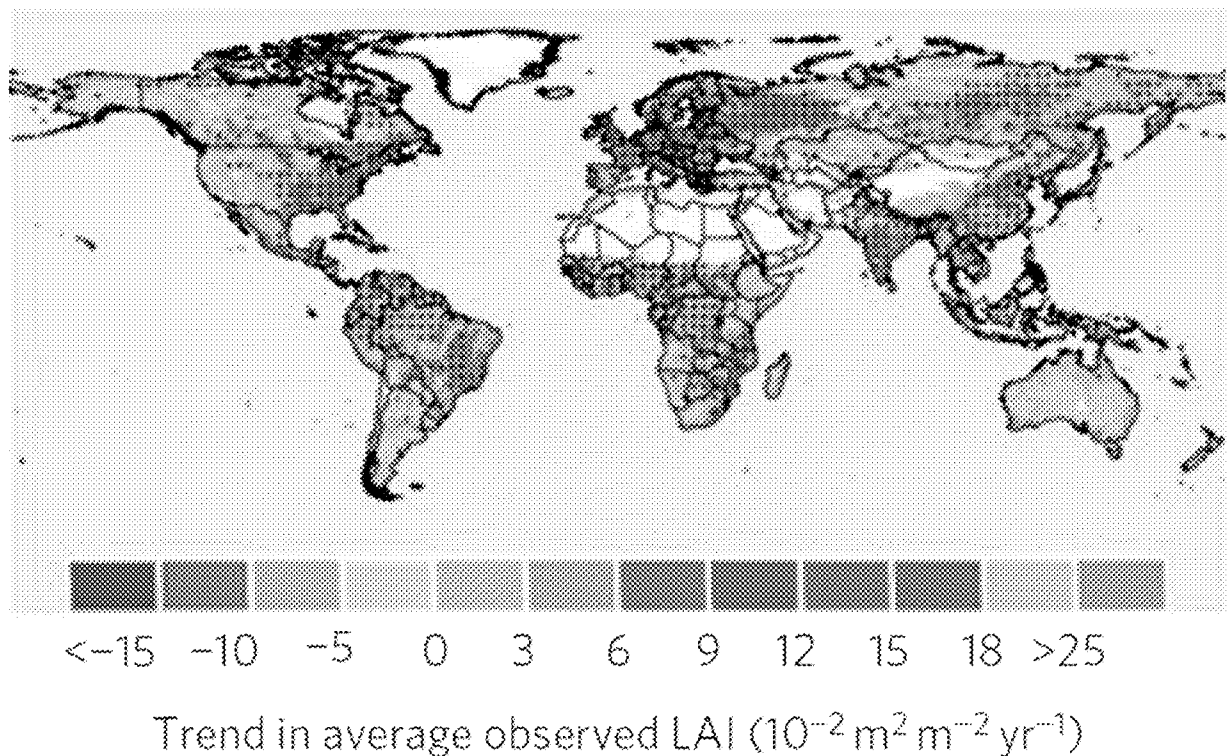


Figure 2.1.1: Trends in average Leaf Area Index (LAI). Source: Zhu et al. 2016 Figure 3.

Zheng (2017) confirmed the pattern, noting that greening over 30 years had added 8% to global leaf area and that greening was mitigating warming. Greening has been observed globally but Chen et al. (2019) noted that China and India were taking particular advantage of it though land management changes.

Thus while China accounts for only 6.6% of global vegetated area it accounts for 25% of global net increase in LAI. Piao et al. (2020) noted that greening was even observable in the Arctic.

While plant models predict increases in photosynthesis should be observed in response to rising CO<sub>2</sub>, Haverd et al. (2020) reported that observed CO<sub>2</sub> fertilization rate was nearly double what models had predicted. That is, CO<sub>2</sub> fertilization had driven an increase in observed global photosynthesis by 30% since 1900, versus 17% predicted by plant models. Among other things this indicates that global models of the socioeconomic impacts of climate change have likely understated the benefits to crops and agriculture from rising CO<sub>2</sub>. The connection between CO<sub>2</sub> fertilization and climate policy will be discussed in Chapter XX.

Finally, Chen et al. surveyed claims that greening had slowed down since 2000 due to drought stress. They found instead that claims of slowed greening could be attributed to faulty satellite sensors. Once the data were corrected they found greening was accelerating over 55% of the world while browning was accelerating over only 7% of the world. Overall the greening trend was continuing with no evidence of slowdown, and CO<sub>2</sub> fertilization remained the dominant driver

## **2.2. Photosynthesis and CO<sub>2</sub> levels**

A key direct effect of adding CO<sub>2</sub> to the atmosphere is its positive effect on plant life via enhancement of photosynthesis and improvement to plant water use efficiency.

The term *photosynthesis* describes the process by which plants build biomass. The process requires carbon dioxide (CO<sub>2</sub>), water (H<sub>2</sub>O), and light. The plant enzyme responsible for photosynthesis is called Ribulose-1,5-bisphosphate-carboxylase/oxygenase or “Rubisco”. Photosynthesis is initiated when CO<sub>2</sub> is available at the surface of the RuBisCo enzyme where it is converted to a molecule with 3 carbon atoms and thereafter incorporated into plant mass, which is referred to as the C3 process.

Rubisco is estimated to have evolved about 3 billion years ago. Over geological time the Earth’s atmospheric CO<sub>2</sub> levels were usually much higher than they are today. About 400 million years ago CO<sub>2</sub> levels were an estimated 2,000-4,000 ppm and were at or above 1,000 ppm for much of the interval from 200 to 50 million years ago (Berner 2006, Judd et al. 2024). Over the past 35 million years the level of atmospheric CO<sub>2</sub> has been steadily declining. During glaciations levels have fallen as low as 170 ppm (Gerhart and Ward 2010). In response to low-CO<sub>2</sub> conditions some plants evolved another photosynthetic pathway called C4, in which CO<sub>2</sub> is concentrated in the vicinity of Rubisco allowing for the C3 process to function more efficiently. For agricultural purposes the plant categories are:

- C3: rice, wheat, soybeans and most other crops
- C4: maize (corn), sugar cane, millet, sorghum

Had atmospheric CO<sub>2</sub> levels continued declining, plant growth rates would have declined and eventually ceased. Below 180 ppm many C3 species experience growth rate reductions on the order of 40-60% compared to their growth rates at 350 ppm (Gerhart and Ward 2010). C3 plants have been observed under experimental conditions to stop growing altogether at levels between 60—140 ppm CO<sub>2</sub>. Some C4 plants are still able to grow at levels even as low as 10 ppm, albeit very slowly (Gerhart and Ward 2010).

Currently, CO<sub>2</sub> levels are about 420 ppm, up from 280 ppm in the early 1800s. The positive response of plants to extra CO<sub>2</sub> is illustrated in Figure 1 which is reproduced from Gerhart and Ward (2010). It shows the growth effect of CO<sub>2</sub> on Velvetleaf (*Abutilon theophrasti*) seedlings over 14 days under controlled conditions where only the CO<sub>2</sub> exposure is varied. The gains exhibited from increasing CO<sub>2</sub> from 150 ppm to 350 ppm continue under a further doubling to 700 ppm.

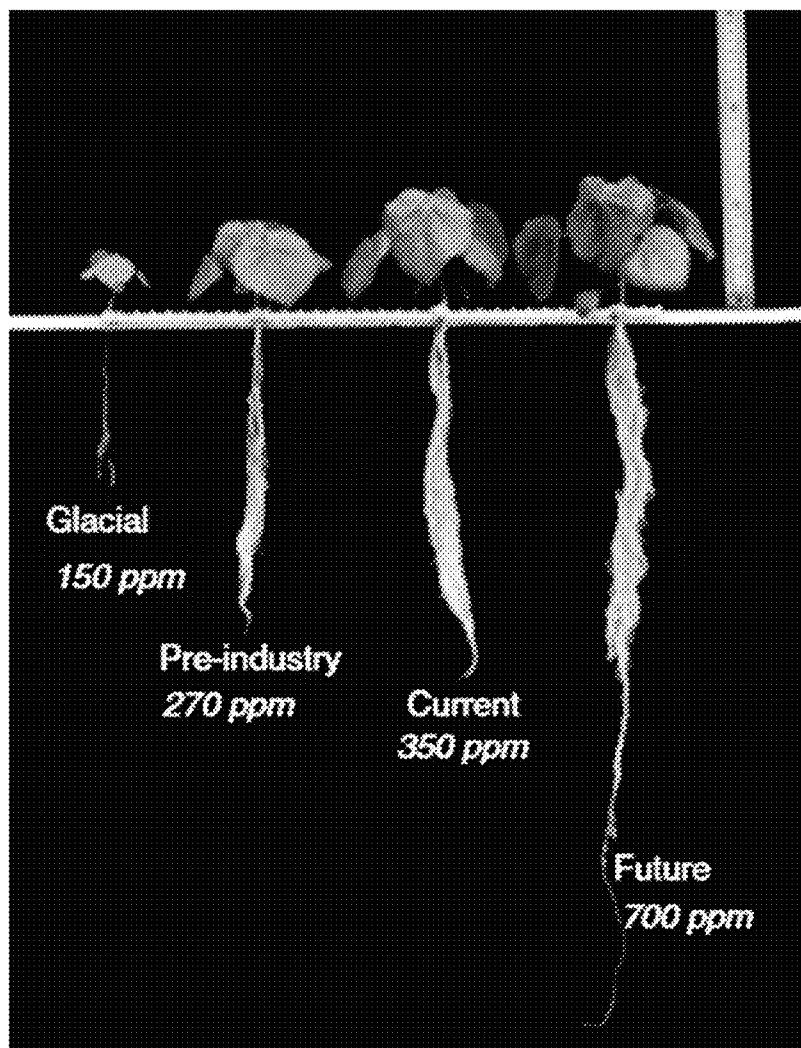


Figure 2.2.1: growth of *Abutilon theophrasti* after 14 days under identical conditions but for the indicated variations in CO<sub>2</sub> levels. Source: Gerhart and Ward (2010).

Over the past 60+ years there have been tens of thousands of studies on the response of plants to rising CO<sub>2</sub> levels. The overwhelming theme is that plants, especially C3 plants, benefit from extra CO<sub>2</sub>. There are two mechanisms by which CO<sub>2</sub> confers a growth benefit:

- Enhanced photosynthesis via the metabolic pathways described above.
- Increased water use efficiency. This arises because plants draw in CO<sub>2</sub> by opening the stomata (pores) on the leaf surface. When CO<sub>2</sub> is scarce the stomata must be kept wide open for long periods, which allows water to evaporate away. Under enriched CO<sub>2</sub> conditions the stomata are closed for longer periods helping the plant retain water longer, thereby increasing water use efficiency.

Specific effects of climate change on US agriculture will be reviewed in Chapter XX.

### **2.3. Rising CO<sub>2</sub> and crop water use efficiency**

Deryng et al. (2016) surveyed evidence on crop water productivity (CWP), i.e. yield per unit of water used, drawing attention to the potential for CO<sub>2</sub> both to enhance photosynthesis and reduce leaf-level transpiration (water loss during leaf respiration). They surveyed all available FACE data on crop yield changes for Maize (corn), Wheat, Rice and Soybean, and combined it with crop model data simulating yield responses as of 2080 under the extreme RCP8.5 scenario in four growing regions (Tropics, Arid, Temperate and Cold) each of which were split into rainfed and irrigated sub-regions. In every region they reported that models without CO<sub>2</sub> fertilization predicted CWP losses but CO<sub>2</sub> fertilization more than offset them and once it was taken into account all regions showed a net CWP gain. Deryng et al (2016) also reported that negative impacts of warming on wheat and soybean yields were fully offset by CWP gains, and mitigated by up to 90% for rice and 60% for maize.

Similar to this, Cheng et al. (2017) noted that increased global plant growth from 1982 to 2011 due to rising CO<sub>2</sub> uptake was accompanied by such large gains in CWP that despite the extra biomass global water use by plants had not increased.

Deryng et al. (2016) assumed that climate change would “exacerbate water scarcity”. It is noteworthy that while models predict drylands will expand under climate warming, current data show the opposite: greening is happening even in arid areas. Zhang et al. (2014) report that due to increased CO<sub>2</sub> levels “increasing aridity in drylands won’t lead to a general loss of vegetation productivity”; increased desertification will happen in at most 4% of currently arid areas.



## 2.4. Concealment of CO<sub>2</sub> fertilization benefits in IPCC Reports

If CO<sub>2</sub> emissions were discovered to be causing global crop declines and regional browning we would almost certainly have seen it discussed prominently in IPCC reports, and indeed it likely would have been the subject of its own chapter in an Assessment Report if not an IPCC Special Report. By contrast the IPCC has been almost silent on the topic of global greening.

The topic is briefly acknowledged in a few places in the body of the IPCC 6<sup>th</sup> and earlier Assessment Reports but is omitted in all Summary documents. Section 2.3.4.3.3 of the AR6 Working Group I report is titled “global greening and browning.” It points out that the IPCC Special Report on Climate Change and Land had concluded with high confidence that greening had increased globally over the past 2-3 decades. It then discusses the various estimate of greening trends, notes that there are variations in the estimates among data sets and then says that while they have *high confidence* greening has occurred, they have *low confidence* in the magnitude of the trend. There are also brief mentions of CO<sub>2</sub> fertilization effects and improvements in water use efficiency in a few other chapters in the AR6 Working Groups I and II Reports.

Overall, however, the Policymaker Summaries, Technical Summaries and Synthesis Reports are conspicuous for their failure to discuss the topic.

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### 3. Increasing CO<sub>2</sub> and the Alkaline Oceans

The modern-day global average pH of sea water is estimated to be 8.1, down from an estimated value of 8.2 in pre-Industrial times (Gattuso and Hansson, 2011). As CO<sub>2</sub> concentrations in the atmosphere increase, more is absorbed by the oceans. Depending upon the alkalinity (buffering capacity) of the oceans, the oceans are expected to become somewhat less alkaline over time, putatively explaining the decrease in pH from 8.2 to 8.1 over the last few hundred years.

While this process is often called “ocean acidification”, this is a misnomer because the oceans are not expected to become acidic (pH less than 7.0). Even if that was to happen, it is believed that life in the oceans evolved during a period when the oceans were mildly acidic, with a pH of 6.5 to 7.0 (Krissansen-Totton et al., 2018).

For many years it was assumed that a decreasing pH of sea water would reduce the calcification rate of coral reefs. But coral reefs already endure large swings in pH, partly due to daily photosynthetic activity in the reef. This results in pH values that have been measured to range from 9.4 during the day to 7.5 at night (Revelle and Fairbridge, 1957).

In 2009 it was reported that a portion of Australia’s Great Barrier Reef (GBR, the world’s largest coral reef ecosystem) had experienced a 14% decline in calcification since 1990 (De’ath et al., 2009). This was tentatively attributed to increasing water temperature and decreasing pH of seawater. But since that time, the initial 2009 report of reduced calcification rates in the GBR was reported to have been the result of a bias in the data analysis (Ridd et al., 2013), and correction for this bias led to no change in calculated calcification rates. Nevertheless, the alarm produced by the original paper has persisted as evidenced by the large number of published citations (541) received by the original study as compared to only 11 citations for the subsequent study (as of 30 April 2025).

Given the reported declines in GBR coverage between 1990 and 2009, it has come as a surprise that the decline reversed over the last decade or so, with Woods Hole Oceanographic Institution asking, “Is the Great Barrier Reef Making a Comeback?” (Woods Hole, 2023). The most recent annual summary of GBR conditions from the Australian Institute of Marine Science was titled, Continued Coral Recovery Leads to 36-year Highs across Two-Thirds of the Great Barrier Reef (AIMS, 2022). Much of the decline in the GBR before 2011 turned out to be due to intense tropical cyclone activity (Beeden et al., 2015), and recovery of the reef from storm damage takes years.

On the time scale of thousands of years, boron isotope proxy measurements of pH show that ocean pH was around 7.4 or 7.5 during the last Ice Age (up to about 20,000 years ago) increasing to present-day values when the world warmed during deglaciation (Rae et al., 2018). Thus, there appears to be considerable resilience of ocean biota to natural long-term changes in ocean pH since marine organisms are exposed to wide ranges in pH anyway.

It is being increasingly recognized that publication bias (alarming ocean acidification results preferred by high-impact research publications) leads to exaggerated impacts from more alkaline oceans. An ICES Journal of Marine Science Special Issue addressed this problem with an article entitled, Towards a Broader Perspective on Ocean Acidification Research. In the Introduction to that Special Issue, H. I. Browman stated, “As is true across all of science, studies that report no effect of ocean acidification are typically more difficult to publish.” (Browman, 2016)

Similarly, a meta-analysis of the negative effects of ocean acidification on reef fishes found that initially dramatic conclusions published in the scientific literature were all but refuted upon subsequent analysis involving larger sample sizes of data (Clements et al., 2021).

In conclusion, it is becoming increasingly apparent that the effect of ocean “acidification” on marine biota has likely been exaggerated.

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## 4. Human influences on the climate

### 4.1. Components of radiative forcing and their history

#### *Historical radiative forcing*

A changing climate has been the norm throughout the Earth's 4.6-billion-year history. The Earth's temperature and weather patterns change naturally over timescales ranging from decades to millions of years. Natural variations in the surface climate originate in two ways. Internal climate fluctuations associated with circulations in the atmosphere and ocean produce exchanges of energy, water, and carbon between the atmosphere, oceans, land, and ice. External influences on the climate system include variations in the energy received from the sun and the effects of volcanic eruptions. Human activities influence climate through changing land use and land cover. Humans are also changing the composition of the atmosphere by increasing emissions of CO<sub>2</sub> and other greenhouse gases and by altering the concentrations of aerosol particles in the atmosphere.

The earth is warmed by the sunlight it absorbs and cooled by the radiative heat it emits to outer space. Averaged over Earth, each of these processes involve power flows of about 240 Watts per square meter (W/m<sup>2</sup>). When they are in balance, there are no net external causes of warming or cooling. Human (and some natural) influences on the climate alter this balance and so cause the climate to change.

Influences on the energy balance are quantified by "radiative forcing", the extent to which they disturb the warming/cooling balance; a positive forcing warms while a negative forcing cools. The IPCC's estimated history of major components of radiative forcing since 1750 is shown in the following two figures from the IPCC AR6.

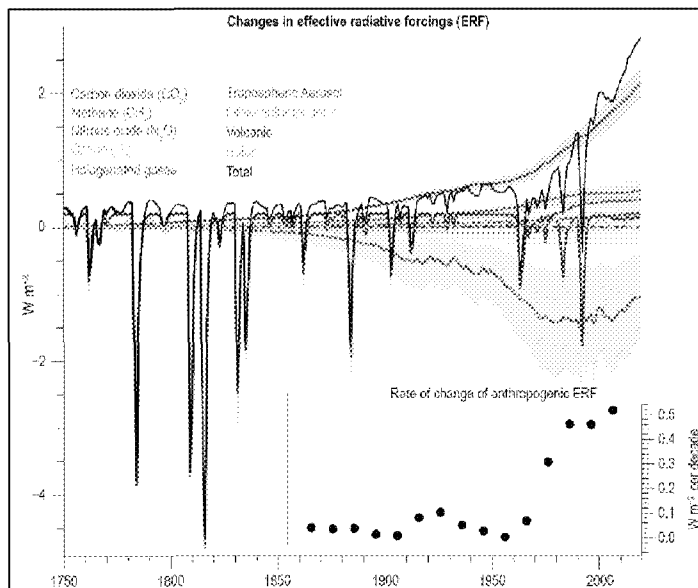


Figure 4.1.1: IPCC estimates of radiative forcing components over time. Source: <https://www.ipcc.ch/report/ar6/wg1/figures/chapter-2/figure-2-10/>

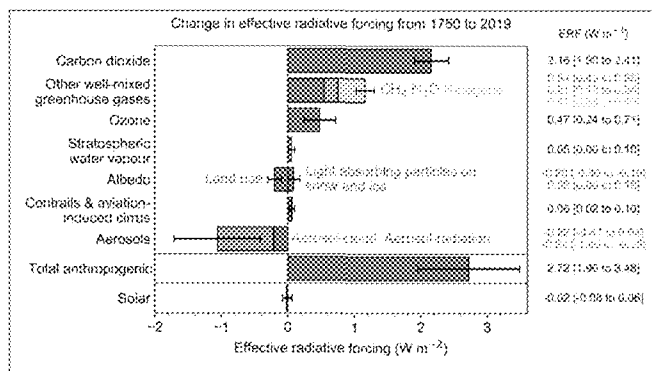


Figure 4.1.2 IPCC estimates of radiative forcing component changes from 1750 to 2019. Source: <https://www.ipcc.ch/report/ar6/wg1/figures/chapter-7/figure-7-6/>

These graphs show that the total radiative forcing is comprised of natural and anthropogenic components. Carbon dioxide is the largest human influence on the climate and the one most relevant to the effects of energy-using systems like motor vehicles. It exerts a warming influence by decreasing the cooling power of the atmosphere. Emissions of CO<sub>2</sub> are accumulating in the atmosphere, as described in the following section, so that the warming influence is increasing. Other greenhouse gases (methane, nitrous oxide, halogens, and ozone), which act similarly, currently add another 75% to CO<sub>2</sub>'s warming. Aerosols exert a cooling effect, although with large uncertainties in the way they catalyze the formation of reflective clouds. As a result, understanding of the causes of recent warming requires not just identifying the warming effects of CO<sub>2</sub>, but also the more uncertain cooling effects of sulfate aerosols.

The IPCC views the role of the sun as negligible, based on their preference for reconstructions that imply minimal solar change since preindustrial times. Connolly *et al.* (2021) reviewed sixteen different Total Solar Irradiance (TSI) reconstructions in the literature covering the 1600-2000 interval; they vary from almost no change in TSI to a relatively large upward trend. Connolly *et al.* point out that the variation in TSI reconstructions combined with variations in surface temperature reconstructions implies pairings can be found that are consistent with either no or most 20<sup>th</sup> century warming being attributable to the sun. A particularly thorny issue is the gap in the TSI data between 1989 and 1991 due to a delay in the launch of a monitor after the Space Shuttle Challenger disaster on January 28 1986, which prevented a replacement satellite from being launched in time to overlap with, and its readings to be intercalibrated with, the prior system (Zacharias 2014, Scafetta et al. 2019). The question of whether there is an upward trend in TSI over 1978 to 2018 comes down to how the missing data in that gap are filled.

The other natural forcing component is largely volcanic aerosols, which exert an episodic cooling influence.

The anthropogenic forcing component was negligible before about 1900 and has increased steadily since, rising to almost 3 W/m<sup>2</sup> today. However, this is still only about 1 percent of the unperturbed radiation flows, making it a challenge to isolate the effects of anthropogenic forcing since state-of-the-art satellite estimates of global radiative energy flows are only accurate to a few W/m<sup>2</sup>. Natural sources of

global energy imbalance other than volcanoes are not included in these graphs because they remain largely unknown.

#### *Future radiative forcing*

Carbon dioxide's warming influence depends upon how much "extra" CO<sub>2</sub> accumulates in the atmosphere- i.e., its concentration. The CO<sub>2</sub> level as recorded at the Mauna Loa observatory in Hawaii is generally used as the representative global average concentration. The data are available online at <https://gml.noaa.gov/ccgg/trends/index.html>. The concentration was about 316 ppm at the start of the record in 1959 and is now about 425 ppm, a 34 percent increase.

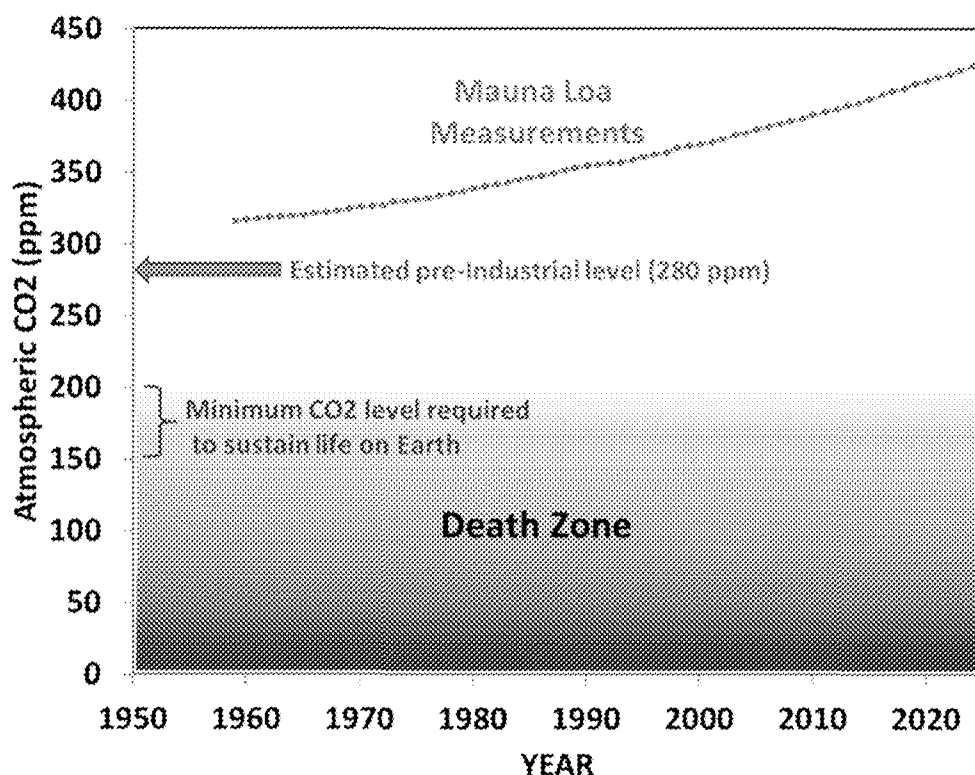


Fig. 4.1.3 Yearly average atmospheric CO<sub>2</sub> concentrations (1959-2024) measured at Mauna Loa, HI (green) compared to the estimated pre-Industrial CO<sub>2</sub> concentration of 280 ppm, and the estimated minimum levels required to sustain life on Earth (150 to 200 ppm). Need source

The annual increase in concentration is only about half of the CO<sub>2</sub> emitted because land and ocean processes absorb "excess" CO<sub>2</sub> at a rate approximately 50% of human emissions. Thus, future concentrations, and hence future human influences on the climate, depend upon two components: (1) future rates of global human CO<sub>2</sub> emissions, and (2) how fast the land and ocean remove extra CO<sub>2</sub> from the atmosphere. We discuss each of these in turn.

## 4.2. Future emission scenarios and the carbon cycle

### *Emission scenarios*

Assessing the future dangers of GHG emissions requires assumptions about what those emissions will be. Future emissions, and hence human influences on the climate, will depend upon future demographics, economic progress, regulation, and the energy and agricultural technologies in use. Various assumptions about each of those lead to projections of greenhouse gas emissions and concentrations, aerosol concentrations, and changes in land use, which ultimately can be combined into assumptions about anthropogenic radiative forcing.

Because of the great uncertainties about these many factors in the decades to come, instead of making precise predictions of future concentrations, the IPCC has created various sets of scenarios meant to span a plausible range of possibilities for population, economy, technology, and so on. Recent versions of the scenarios are labeled by a number indicating the anthropogenic radiative forcing expected in 2100 under that scenario. Thus, a scenario labeled with a “6” corresponds to 6 W/m<sup>2</sup> of human-induced radiative forcing (warming) at the end of the century. (Recall current anthropogenic radiative forcing is about 2.7 W/m<sup>2</sup>.)

Although the IPCC does not put its emission scenarios forward as forecasts they are often treated as such. Comparisons of past scenario groups against observations shows a tendency for IPCC emission projections to overstate actual subsequent emissions. For the IPCC Third and Fourth Assessment Reports a set of emission projections from the *Special Report on Emission Scenarios* were used and hence were referred to as the SREP scenarios. McKittrick *et al.* (2012) showed that, when converted to per capita terms, the SREP scenario distribution was skewed upwards and incompatible with observed trends. McKittrick and Wood (2013) further showed that global energy market dynamics constrained global per capita CO<sub>2</sub> emissions to an extent not reflected in IPCC scenarios. The bias of the SRES scenarios was confirmed by the later analysis in Hausfather *et al.* (2019) who showed that observed atmospheric CO<sub>2</sub> concentrations tracked the low end of the SRES range.

For the Fifth Assessment Report the IPCC developed a new set of scenarios called the Representative Concentration Pathways (RCP). These were identified by a number representing the increase in forcing and were thus called RCP2.6, RCP4.5, RCP6.0 and RCP8.5. RCP2.6 (implying a radiative forcing in 2100 of 2.6 W/m<sup>2</sup>) projects a GHG concentration pathway leading to warming well below 2 C. At the other end of the scale RCP8.5 is an extreme outcome implying nearly 5 C warming just in this century.

RCP8.5 came to be referred to as the no-policy baseline, or “business-as-usual” scenario in both the academic literature and popular media. It was therefore used to generate the reference outcome supposedly representing the 21<sup>st</sup> century world in the absence of emission reduction policies. But RCP8.5 was intended as a low-probability high emissions scenario and its usage as a business-as-usual baseline has been criticized as grossly misleading.<sup>1</sup> Hausfather and Peters (2020) writing in a commentary in *Nature* magazine, pointed out that RCP8.5 was developed as an extreme worst-case, and its misuse as a “business as usual” baseline has resulted in a large number of misleading studies and media reporting:

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<sup>1</sup> This extreme scenario is useful for modelers, since a large forcing generates a large response (warming) making it easier to assess a model’s sensitivity. But that’s very different than claiming it is a plausible future.



RCP8.5 was intended to explore an unlikely high-risk future. But it has been widely used by some experts, policymakers and the media as something else entirely: as a likely ‘business as usual’ outcome. A sizeable portion of the literature on climate impacts refers to RCP8.5 as business as usual, implying that it is probable in the absence of stringent climate mitigation. The media then often amplifies this message, sometimes without communicating the nuances. This results in further confusion regarding probable emissions outcomes, because many climate researchers are not familiar with the details of these scenarios in the energy-modelling literature. (Hausfather and Peters 2020)

The implausibility of the RCP8.5 scenario was examined by Burgess *et al.* (2021). They noted that RCP8.5 has already diverged from observed energy use trends, and the near future trends diverge sharply from those of the International Energy Agency (IEA) which provides market-based projections of energy use for coming decades. IEA trends are based on plausible extrapolations of current economic and demographic trends, and the results run below the entire envelope of RCP projections, implying not only that RCP8.5 is dubious, but even lower emission scenarios are looking unlikely. Burgess *et al.* comment (p. 8):

Beyond 2040, if the trends anticipated by energy agency forecasts continue, carbon intensity will continue diverging from AR5 and SSP baselines—especially from higher-emission scenarios such as RCP8.5, due to the assumptions about fossil-fuel expansion in these scenarios that are increasingly implausible.

Widespread use of RCP8.5 has created an alarmist bias in the climate impacts literature. The extent of this problem was confirmed in a literature analysis by Pielke Jr. and Ritchie (2020). They found (p. 32) that some 16,800 scientific papers published between 2010 and 2020 used the RCP8.5 scenario, with about 4,500 of the articles (p. 16) linking RCP8.5 with the concept of “business-as-usual”. Their analysis showed how RCP8.5 was misused not only by individual researchers, but also by influential science agencies like the IPCC and the US National Climate Assessment (USNCA), which has directly led to misleading coverage in prominent media outlets. They offer the following example (p. 30):

The USNCA employed RCP8.5 as a baseline scenario, despite warning against such use, and compared it to RCP4.5 throughout its report to generate quantitative economic estimates of the benefits of mitigation. In a front-page story, the *New York Times* promoted the report’s misuse of RCP8.5 as a baseline scenario:

“A major scientific report issued by 13 federal agencies on Friday presents the starkest warnings to date of the consequences of climate change for the United States, predicting that if significant steps are not taken to rein in global warming, the damage will knock as much as 10 percent off the size of the American economy by century’s end.”

Pielke and Ritchie (2020) reported new studies using RCP8.5 were appearing in the literature at a rate of about 20 per day, with about two per day specifically linking RCP8.5 and “business as usual.” They conclude (p. 34) that the climate research community has spent a decade “committing scientific resources to science fiction” (emphasis added):

“Derived estimates from RCP8.5 as “business as usual” such as future climate impacts, the impacts avoided from mitigation and the cost effectiveness and benefits of mitigation have no real-world meaning... **The scientific literature has become imbalanced in an apocalyptic direction.**

(Pielke Jr. and Ritchie p. 34)

The IPCC later converted the RCP scenarios to the “Shared Socioeconomic Pathway” or SSP scenarios, but these have continued the pattern of bias shown with the RCP and SRES scenarios. Figure 3.1.4 was generated using the Resources for the Future Global Energy Outlook tool (RFF 2025). The black line shows total global observed CO<sub>2</sub> emissions compiled by the International Energy Agency (IEA). The solid green line is the emission trajectory developed by BP Energy taking account of current emission control policies and global energy use outlooks. It overlaps a solid black line which represents the emission projection from the IEA also taking account of energy use projections and current policies. The dashed lines show the range of IPCC SSP policies. As of 2023 global CO<sub>2</sub> emissions have been tracking well below the SSP scenarios especially the two highest ones (SSP5-8.5 and SSP3-7.0).

**Carbon dioxide emissions (Million metric tons), by Outlooks & Scenarios. Filtered by Region: World; Fuel: All; Outlook: 2023 Shell (Sky 2050).**

Source: RFF Global Energy Outlook at [www.rff.org/glo](http://www.rff.org/glo)

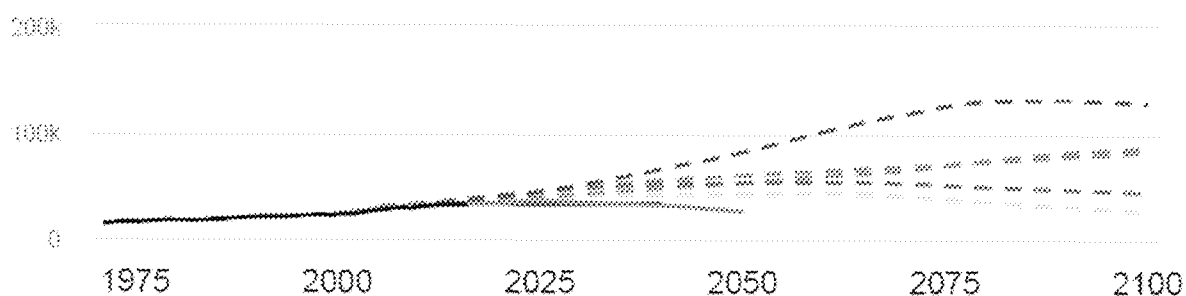


Figure 4.2.1. Observed and projected CO<sub>2</sub> emissions. Source: RFF (2025).

### *The carbon cycle relating emissions and concentrations*

Global carbon cycle models relate concentrations to emissions using estimates of various land and ocean processes that remove CO<sub>2</sub> from, and emit CO<sub>2</sub> into, the atmosphere. Our understanding of these processes was reviewed by Crisp et al. (2021). The natural fluxes of CO<sub>2</sub> in and out of the Earth’s surface are very large, many times anthropogenic emissions, but those CO<sub>2</sub> sources and sinks were assumed to be in approximate balance in pre-Industrial times, as evidenced by relatively constant levels of

atmospheric CO<sub>2</sub> in centuries past derived from air bubbles in ice cores. This is one of several reasons why increasing atmospheric CO<sub>2</sub> levels are believed to be dominated by anthropogenic sources.

Specifically, fossil fuel burning (and to a lesser extent land use [biomass burning] and cement production) has led to steadily increasing CO<sub>2</sub> levels in the atmosphere, as shown in Fig. 1.2.1. CO<sub>2</sub> emissions from fossil fuel burning is a small fraction of the natural carbon cycle components. About 44,000 Gigatonnes of carbon-equivalent (GtC) are stored in the atmosphere and oceans, mostly in the form of CO<sub>2</sub>. (Ciais et al. 2013). Between 150 and 200 GtC are released naturally each year through oceanic outgassing and land-based processes like plant decay and animal respiration. A variable but roughly equivalent amount is absorbed each year by the land and oceans, with a small net loss from the atmosphere because the formation of deep ocean sediment sequesters some carbon permanently. Global fossil fuel consumption and cement manufacture released about 10.3 GtC in 2023, up from 6.2 GtC in 1990 (Ritchie et al. 2024). Of this, about half is naturally sequestered through plant growth and oceanic uptake while the remainder, about half, adds to the atmospheric stock (Ciais et al. 2013).

As noted, each year natural processes remove a net amount of CO<sub>2</sub> equivalent to about 50% of global emissions. Thus, anthropogenic CO<sub>2</sub> emissions average twice what is required to explain the atmospheric rise in CO<sub>2</sub> concentration. The near-constancy of that 50% fraction (the “airborne fraction”) also means that the more CO<sub>2</sub> humanity produces, the faster nature removes it from the atmosphere. That 50% fraction changes somewhat from year to year due to natural carbon cycle imbalances from El Nino, La Nina, and varying weather patterns. There was also a substantial additional reduction in atmospheric CO<sub>2</sub> after the 1991 eruption of Mt. Pinatubo, a curious result that has yet to be explained (Angert et al., 2004).

The main processes which remove excess CO<sub>2</sub> from the atmosphere are increased production of land vegetation (especially at high latitudes), some increase in the sequestering of carbon in soils, and uptake of CO<sub>2</sub> by the ocean due to the increasing partial pressure of atmospheric CO<sub>2</sub> over that of CO<sub>2</sub> dissolved in the ocean. All twenty land carbon cycle models tracked by the Global Carbon Project (Friedlingstein et al., 2024) show land processes have been removing excess CO<sub>2</sub> at an increasing rate since 1959. This is consistent with a “global greening” phenomenon observed by satellites since monitoring of global greenness began in the 1982. This greening has been traced to CO<sub>2</sub> fertilization and greater drought tolerance of plants exposed to elevated CO<sub>2</sub> levels. While there had been some uncertainty whether a greening trend continued beyond 2000, the most recent research (Chen et al., 2023) has shown continued greening, with even some slight acceleration since 2000. Global greening is discussed further in Section 3.1.

While land vegetation has been responding positively to more atmospheric CO<sub>2</sub>, uptake of extra CO<sub>2</sub> by ocean biological processes remains too uncertain to be reliably measured. Our current understanding of these and many more carbon cycle processes was reviewed by Crisp et al. (2021).

Public policy can only change the rate of emissions, not the concentration in the atmosphere. For criteria air contaminants the rate and concentration are closely connected because the lifetime is short and the concentration is small. When emissions are reduced the local pollution concentration drops rapidly, usually on a time scale of a few days. Not so with the global average CO<sub>2</sub> concentration since global carbon cycle is vast and slow. A change in local emissions today will only have a very small global effect, and only after a long time lag. After a pulse (release) of CO<sub>2</sub> emissions to the atmosphere only about 40 percent ( $\pm 15\%$ ) of the extra CO<sub>2</sub> will have been sequestered after twenty years. After a

thousand years about 75 percent ( $\pm 10\%$ ) will have been sequestered, and the remainder will gradually be removed over the ensuing tens of thousands of years (Ciais et al. 2013, pp. 472-473). Consequently US CO<sub>2</sub> emission reductions will take decades or centuries to lead to a reduction in the global CO<sub>2</sub> concentration.

To reduce the atmospheric stock of CO<sub>2</sub>, assuming the entire increase is anthropogenic, would require emissions to fall below the natural sequestration rate. Since that rate has been averaging about 50% of emissions, a reduction of global emissions by 50% would (at least temporarily) halt the rise in atmospheric CO<sub>2</sub>. The 1997 Kyoto Protocol proposed to cap industrial nations' CO<sub>2</sub> emissions at a modest five percent below 1990 levels by the year 2012. Even though this policy ended up too costly for most nations to implement, full compliance would not have substantially reduced atmospheric CO<sub>2</sub> levels. It would only have slightly slowed CO<sub>2</sub> growth, reaching the projected 2100 level in 2105 instead (Wigley 1998). Similarly, Lomborg (2016) used the widely-used MAGICC climate model and showed that full compliance with the Paris Accord would not stop warming, it would only prevent about 0.1C warming and delay hitting the baseline year 2100 temperature levels by about a decade.

Thus, in contrast with conventional air pollution control, local actions yield extremely small local effects, and only after a long time lag. The practice of referring to unilateral US reductions as “combatting climate change” or “taking action on climate” reflects a profound misunderstanding of the scale of the issue. As will be discussed in Chapter 14, the scale problem is compounded by recognizing that US motor vehicles account only for about 4 percent of global CO<sub>2</sub> emissions so even a fifty percent reduction in those emissions would have a vanishingly small effect on the global climate.

#### **4.3. Aerosols and the uncertainties associated with them**

The climate's sensitivity to CO<sub>2</sub> (as quantified by ECS, the Equilibrium Climate Sensitivity<sup>2</sup>) is uncertain because the net forcing results from (at least) two counteracting components: warming from GHG's and cooling from aerosols. The observed warming can therefore be made to be consistent with a wide range of pairs of these forces. In the following schematic, the net warming represented by the red arrow could be due to the High GHG warming/strong aerosol cooling pair, or the Low GHG warming/weak aerosol cooling pair, or something in between.

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<sup>2</sup> ECS is formally defined as the increase in equilibrium global average surface temperature resulting from a doubling of the atmospheric CO<sub>2</sub> concentration above its pre-industrial value of 280 ppm. Estimates of ECS are reviewed in Section XX.

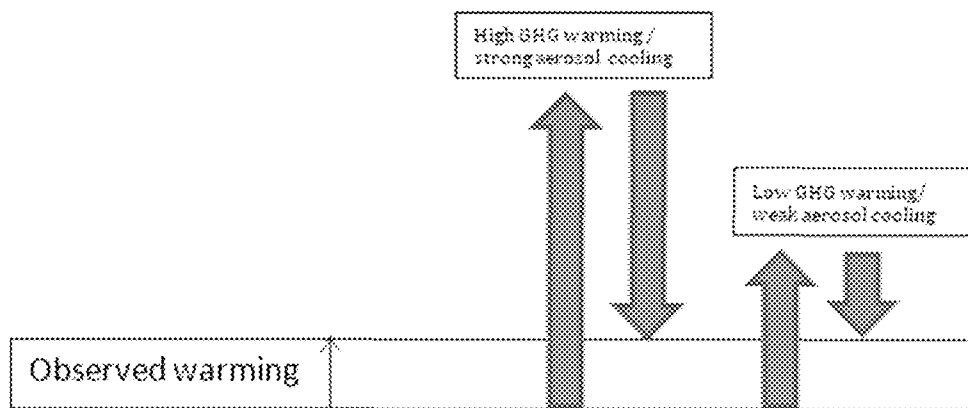


Figure 4.3.1: High and low climate sensitivity to GHGs can be reconciled with the same warming by assuming an offsetting aerosol cooling effect.

Research on the strength of aerosol cooling is therefore central to more precise ECS estimates. Lewis and Curry (2018) note that after the IPCC AR5 was published in 2013, eleven studies appeared in the scientific literature all finding that aerosol cooling was weaker than had previously been conjectured. Combining the updated aerosol estimates with greenhouse gas, ocean heat uptake and atmospheric warming data from the IPCC and applying standard empirical methods, Lewis and Curry (2018) estimated the best-guess ECS to be 1.66°C with a 95 percent uncertainty range of 1.15 °C – 2.7°C. They concluded that based on the ECS values derived from most IPCC climate models were incompatible with observed data.

There has been further evidence of lower aerosol cooling (implying lower ECS) such as Liu et al. (2021). These authors tested the hypothesis that aerosols from wildfires has increased since before the 20<sup>th</sup> century which, if true, would mean there had to have been relatively strong CO<sub>2</sub> warming over that period offsetting the aerosol cooling. They examined soot layers in ice cores extracted from Antarctica and South America and determined that wildfire activity prior to the 20<sup>th</sup> century was higher than previously believed. Instead of wildfire activity rising steadily from the 1700s to the present, it was high all the time, thus contradicting the hypothesized aerosol cooling trend in the Southern Hemisphere during the 20<sup>th</sup> century. They pointed out how this finding relates to the climate sensitivity issue:

Accurate estimates of aerosol radiative forcing are also crucial for better understanding the transient climate response (TCR) and equilibrium climate sensitivity (ECS) to increasing CO<sub>2</sub> and more accurate projection of future climate change. The negative aerosol radiative forcing can, in part, cancel out the positive forcing of increasing greenhouse gases and contribute to the uncertainty of total radiative forcing. An overly large aerosol cooling implies that models might overestimate TCR and ECS to reproduce historical temperature response. A recent study using one of the latest-generation CMIP6 climate models (E3SM) suggested that reducing both the magnitudes of negative aerosol radiative forcing and climate sensitivity yields a better agreement with the observed historical record of the surface temperature.

(Liu et al. 2021)

More evidence pointing to weak aerosol cooling was reported by Wang *et al.* (2021). They noted that the strength of aerosol cooling is partly mediated by cloud behavior and differs between the North and South Hemispheres because of the different density of aerosol emissions. This allowed them to construct another test of climate model validity, which came out in favor of low ECS models. In their words:

Since anthropogenic aerosols primarily concentrate in the Northern Hemisphere, strong aerosol-cloud interaction models produce an interhemispheric asymmetric warming. We show that the observed warming asymmetry during the mid to late 20th century is more consistent with low ECS (weak aerosol indirect effect) models.

Wang et al. (2021)

To summarize, quantifying warming due to CO<sub>2</sub> requires understanding the strength of aerosol cooling. While that latter is uncertain a substantial body of recent evidence points to it being relatively weak, implying that CO<sub>2</sub> warming is likewise weak.

## Summary

- The global climate is naturally variable. Anthropogenic CO<sub>2</sub> emissions add to that variability by changing the total radiative balance in the atmosphere.
- The IPCC has downplayed the role of the sun in climate change but there are Total Solar Irradiance reconstructions that imply it might have been important, and the modern record is uncertain due to an interruption in satellite coverage.
- Projections of anthropogenic emissions are combined with carbon cycle model estimates of atmospheric CO<sub>2</sub> removal to estimate future CO<sub>2</sub> concentrations and hence the radiative forcings. These are input to climate models to estimate future anthropogenic changes in the climate.
- IPCC emission scenarios envelopes have tended to exceed observed trends.
- The vast majority of academic climate “impacts” studies in recent years are based upon the extreme RCP8.5 scenario that is considered implausible; its usage as a business-as-usual scenario is misleading.
- Despite ample evidence that scenario envelopes are exaggerated, and despite criticism of this practice in the peer-reviewed literature, the IPCC’s most recent scenario set (SSP) perpetuates this malpractice.
- The global carbon cycle heavily dampens the effect of changes in local (e.g. U.S.) CO<sub>2</sub> emissions. Even global-scale emission reductions will have only small, much delayed effects.
- Knowing the magnitude of CO<sub>2</sub> warming requires knowing the strength of aerosol cooling. While that is uncertain, a substantial body of recent evidence points to it being relatively weak, implying CO<sub>2</sub> warming is likewise weak.

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## Part II: Climate Response to Greenhouse Gas Emissions



## 5. Climate Sensitivity to CO<sub>2</sub> Forcing

### 5.1. Introduction

The sensitivity of Earth's climate to increasing concentrations of CO<sub>2</sub> is at the heart of the scientific debate on anthropogenic climate change, and also the public debate on the appropriate policy response to increasing CO<sub>2</sub> in the atmosphere. Equilibrium Climate Sensitivity (ECS) refers to the expected amount of warming averaged over the Earth's surface in response to a doubling of CO<sub>2</sub>, after all climate systems have had time to adjust. Some systems, like temperatures in the troposphere, adjust very rapidly, whereas others such as the deep ocean and ice sheets may take decades or even centuries. A related metric which is helpful for analysis on shorter time scales is the Transient Climate Response (TCR), defined as the amount of warming after 70 years in which atmospheric CO<sub>2</sub> increases by one percent annually.

In 1979 the Charney (1979) Report for the US National Academy of Sciences proposed that the most likely value for ECS was 3.0°C plus or minus 1.5°C. The ECS range between 1.5 and 4.5°C is characterized by the IPCC AR5 as the likely range (66 percent probability); the AR5 stated that ECS is extremely unlikely (95 percent probability) to be below 1.0°C and very unlikely (90 percent probability) to exceed 6.5°C. This range of ECS values has remained stubbornly wide, despite many individual studies claiming to narrow it. Most recently, the IPCC AR6 narrowed its assessment of the likely range of ECS to 2.5–4.0°C and the very likely range to be between 2.0 and 5.0°C. This narrowing of the range on the low end is disputed, as will be discussed below.

Uncertainties about ECS are highly consequential for policy making. As will be discussed in Chapter 13, economic models take the ECS value from climate science and use it to project the costs of CO<sub>2</sub> emissions. The traditional ECS value (3.0 °C) has typically yielded modest global social costs of CO<sub>2</sub> emissions, enough to justify some policy actions though mostly deferred to later in the century. If ECS is very high (4.5°C or above) aggressive immediate emission controls become more imperative, whereas values closer to 2.0°C have been shown to imply that no CO<sub>2</sub> emission controls are economically justifiable (Dayaratna et al. 2016, 2020). Obtaining a precise estimate is impossible, so policy making needs to account for the uncertainty.

### 5.2. Model-based methods of computing climate sensitivity to GHGs

The ECS ranges for the IPCC AR4 and AR5 were obtained primarily by examining the behaviour of climate models. For the AR6 the IPCC changed course and turned to a more direct data-driven methodology. Here we discuss some of the pitfalls of using climate models to try to determine the Earth's climate sensitivity.

ECS represents an emergent property of climate models—that is, it is not directly parameterized or tuned. However, collections of parameterizations are often chosen to produce an expected value of climate sensitivity, particularly with regards to sub-grid-scale cloud processes. Otherwise plausible models and parameter selections have been discarded because of perceived conflict with this warming rate, or aversion to a model's climate sensitivity being outside an accepted range. For example,

Mauritsen and Roeckner (2020) state the following regarding their Max Planck Institute climate model (emphasis added):

“We have documented how we tuned the MPI-ESM1.2 global climate model to match the instrumental record of warming; an endeavor which has clearly been successful. Due to the historical order of events, the choice was to do this practically by targeting an ECS of about 3 K using cloud feedbacks, as opposed to tuning the aerosol forcing.”

In other words, the modelers chose an ECS value of 3°C and then tuned the cloud parameterizations to match their intended result.

Direct warming from CO<sub>2</sub> doubling is only about 1°C (Hall and Manabe 1997); further warming arises from climate feedbacks that are not explicitly resolved by the model but rely on parameterizations of physical processes. Higher values of ECS arise primarily from positive cloud feedbacks whose magnitude and even sign are very uncertain. Elements of cloud feedback include changes in the latitudinal distribution of clouds, changes in the distribution of cloud height (changes in low versus high clouds), changes to the phase of clouds (ice versus liquid), changes in cloud particle size (associated with changes in concentration and/or composition of aerosol particles), changes in the precipitation efficiency of clouds, and even changes in how clouds are distributed over the daily solar cycle (Curry and Webster, 1999). It is difficult for climate models to simulate any of these processes correctly owing to their small scale, let alone predict how they will change in the future. Further, cloud processes modulate the magnitudes of the water vapor, lapse rate, and the surface albedo feedbacks.

ECS can be determined from climate model simulations by doubling the concentration of CO<sub>2</sub> and allowing several centuries for the warming to equilibrate. To avoid the necessity of long simulations, “effective climate sensitivity” is commonly evaluated from a 150-year simulation in response to a sudden quadrupling of CO<sub>2</sub>. The spread of ECS values from the CMIP5 climate models (used in the AR5) was 2.0–4.7°C; the spread has increased for the CMIP6 models (used in the AR6) to between 1.8 and 5.7°C (Chen et al, 2021). Far from the science being settled in relation to the response of the climate system to increasing greenhouse gas concentrations, insofar as it is represented by climate models, uncertainties appear to be growing. The main cause of the overall upward shift in ECS in CMIP6 relative to CMIP5 is a larger positive cloud feedback, driven by changes to the cloud parameterizations in many CMIP6 models (Zelinka et al., 2020)

Because of concerns about model tuning and the high sensitivity to cloud parameterizations, the IPCC AR6 (2021) did not rely on climate model simulations in their assessment of climate sensitivity, relying instead on other methods in its assessment instead, chiefly a recent empirical estimate.

### **5.3. Data-driven methods of computing climate sensitivity to GHGs**

Climate sensitivity can also be estimated from instrumental records of surface temperatures and ocean heat content, combined with estimates of how climate forcings (e.g., greenhouse gases, solar, volcanoes,

aerosols) have changed in the past (Otto et al., 2013). Using this information, a simple empirical model called an Energy Balance Model can be estimated. It requires estimating a feedback parameter whose uncertainties are highly amplified in the resulting ECS (Roe and Baker, 2007).

The accuracy of the data-driven methods depends on the quality of the input data. Assumptions are needed about ocean heat storage, and the ocean data is inadequate. The greatest source of uncertainty is the amount and composition of aerosol particles and their interactions with cloud radiative properties (the so-called aerosol indirect effect). Climate models exhibit warming in response to GHGs but cooling in response to aerosols (Schwartz et al. 2007). Observed 20th century warming can be shown to be consistent either with low ECS and low aerosol cooling, or high ECS and high aerosol cooling. Since fossil fuel use adds both GHGs and aerosols to the atmosphere, both effects need to be estimated to isolate the warming effect of CO<sub>2</sub>. Over time, the IPCC's estimate of the cooling effect of aerosols has declined (Lewis 2022).

Paleoclimate proxies are also used to evaluate the sensitivity of past climates, by comparing paleoclimate changes in the Earth's temperatures to estimates of changes in forcings. The two most informative periods are the last glacial maximum (around 20,000 years ago), which was about 3–7°C colder than today, and a mid-Pliocene period (roughly three million years ago), which was 1–3°C warmer than today. The limits on cooling during the last glacial maximum give the best single evidence that high values of climate sensitivity are unlikely. However, paleoclimate estimates are associated with very large uncertainties in the estimated temperatures and forcings. Further, estimates of climate sensitivity based on past climate states may not be representative of the current state of the climate system.

A recurring theme in the climate literature is that ECS estimates based on historical data are smaller than ECS estimates inferred from climate models (Sherwood and Forest 2024). About 15 estimates based on historical data appeared in the peer-reviewed literature between 2012 and 2024 yielding ECS best estimates between 1.0°C and 2.5°C, although critics have questioned some of the methods and the data quality. For the AR6, the IPCC placed primary weight on the results of Sherwood et al. (2020) that combined historical and paleoclimate proxies and yielded a best estimate of 3.1°C. Lewis (2022) raised a number of concerns about this result, including methodological errors, outdated input values, and use of subjective versus objective Bayesian priors in the analysis. Lewis' analysis found that climate sensitivity is estimated to be much lower and better constrained than in the Sherwood et al. analysis – median 2.2°C (1.8–2.7°C in the 17–83 percent likely range, and 1.6–3.2°C in the 5–95 percent very likely range). The IPCC AR6 estimated only a 5 percent probability that ECS was below 2.3°C, whereas Lewis estimated it to be over 50 percent. The most recent publications on the debate between Sherwood et al. and Lewis further defend their respective positions: Sherwood and Foster (2024) and Lewis (2025).

An interesting footnote is that in 1983, the US National Research Council conducted a follow-up study to the 1979 Charney Report, and referring to the estimated sensitivity range of 1.5°C to 4.5°C, said:

“The climate record of the past hundred years and our estimates of CO<sub>2</sub> changes over that period suggest that values in the lower half of this range are more probable.”

Nierenberg et al. (1983 p. 2)

Lewis' analysis likewise implies that climate sensitivity is likely in the lower half of the original 1979 Charney range.

A recent argument, which the IPCC AR6 emphasized, is that data-driven ECS estimates might understate the future warming response to GHGs based on a so-called “pattern effect” (Forster et al 2021). The tropical Pacific is believed to be highly influential on the overall efficiency with which the Earth's climate radiates heat to space, but in some regions heat is more efficiently removed from the climate system than from others. If in a warming climate there is a weakening of the west-to-east temperature gradient in the tropical Pacific, the result would be a concentration of warming in a region where heat is less efficiently removed, raising the ECS of the Earth's climate system. Most climate models simulate that rising GHGs will weaken the east-west temperature gradient, which led the IPCC in the AR6 to conclude that data-driven ECS estimates understated the future ECS value.

However, Seager et al. (2019) pointed out that, contrary to models, the east-west temperature gradient has been strengthening rather than weakening over time. They further argued that the mechanism predicting otherwise in climate models was based on a faulty characterization of oceanic dynamics and there is no reason to expect the gradient to weaken. A similar argument was recently made by Lee et al. (2024), who concluded that “the trajectory of the observed trend reflects the response to increasing GHG loading in the atmosphere”; in other words, GHG warming should lead to a future strengthening rather than a weakening of the temperature gradient. Increased efficiency of atmospheric cooling implies, if anything, that the future ECS in a warming climate may be lower than current estimates.

#### **5.4. Transient Climate Response**

The Transient Climate Response (TCR) is of greater utility in providing an observational constraint on climate sensitivity. TCR is the amount of warming that would occur at the time when CO<sub>2</sub> doubles, having increased gradually by 1 percent each year over a period of 70 years. Relative to the ECS, observationally-determined values of TCR avoid the problems of uncertainties in ocean heat uptake and the fuzzy boundary in defining equilibrium arising from a range of timescales for the longer-term feedback processes (e.g., ice sheets). TCR is more generally related to peak warming and better constrained by historical warming, than ECS. The IPCC AR6 judged the very likely range of TCR to be 1.2–2.4°C. In contrast to ECS, the upper bound of the TCR is more tightly constrained. For comparison, the TCR values determined by Lewis (2023) is 1.25 to 2.0°C, showing much better agreement with the AR6 values than was seen in a comparison of the ECS values.

A related but more flexible parameter is the Transient Response to cumulative carbon Emissions, or TCRE, which relates global temperature change to the cumulative emissions. TCRE is based upon a linear relationship between global average temperature and cumulative emissions, which holds for cumulative emissions of up to 2 teratons of carbon. For a given value of TCRE, we can estimate the amount of warming expected over a future period in response to scenarios of cumulative carbon emission. The IPCC AR6 provides a very likely range for TCRE of 1.0–2.3°C, with a median value of 1.6°C.<sup>48</sup>

As will be discussed in Chapter 6, a real-world ECS below the model average is supported by studies which show climate models on average estimate too much warming at the surface and in the troposphere compared to observations over the past 50 years. Also, lower values align with evidence from consistent fingerprinting (Section 8) that model responses to GHGs need to be scaled down quite a bit to align with observed trends.

## 5.5. Summary

In the past 5 years, there is a growing realization that climate models are not fit for the purpose of determining the sensitivity of the climate to increasing CO<sub>2</sub> (ECS), owing to the dependence of this sensitivity on poorly resolved processes related to clouds and water vapor.

Data-driven approaches using historical data and paleoclimate reconstructions are now regarded as more reliable for determining ECS, but their reliability is diminished by data inadequacies. The IPCC AR6 upper bound for the likely range of ECS is 4.0°C, lower than the AR5 value of 4.5°C. This lowering of the upper bound seems well justified by the paleoclimatic estimates of the ECS. The IPCC AR6 lower bound for the likely range of ECS is 2.5°C, substantially higher than the AR5 value of 1.5°C. This raising of the lower bound of the likely range of ECS has received a substantial challenge from the analysis of Lewis (2022, 2025) that finds the lower bound of the likely range to be 1.75°C with a median value of 2.2°C. Other lines of evidence supporting a lower bound on the ECS range below the IPCC AR6 value are discussed in Chapters 6 and 7.

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## 6. Models versus Observations in the Recent Past

### 6.1. Introduction

Climate models are the primary tool used to project future climate changes in response to increasing atmospheric levels of anthropogenic greenhouse gases. They provide the theoretical evidence underpinning energy policy changes, such as efforts to reduce carbon dioxide emissions. In order to determine the value of climate models for this purpose, it is reasonable to ask how well they have reproduced climate variations over the recent past, say the last half-century.

Of great concern is the fact that, after several decades of the climate modeling enterprise involving approximately three dozen models operated by research centers around the world, the range of future warming they produce in response to a hypothetical doubling of atmospheric CO<sub>2</sub> extends over a factor of three. This range of disagreement among models has not changed for decades.

Problems with climate models are not just in their disagreement over the future, but also in their ability to replicate the recent past. Here we review some of the most important metrics of climate model accuracy: ability to reproduce historical surface, tropospheric and stratospheric temperature trends, ability to reproduce the vertical warming profile and ability to reproduce other climate features such as snowfall and humidity. In all cases a persistent finding is that models on average err on the side of too much warming in response to observed historical forcings.

### 6.2. Surface warming

A straightforward test of climate model validity is its ability to reproduce historical warming in response to known past changes in climate drivers such as greenhouse gases. Figure 6.1 is reproduced from Scaffeta (2023), a peer-reviewed 2023 study which groups the latest-generation (CMIP6) climate models into low ECS (1.5 to 3.0 degrees C), medium ECS (3.0 to 4.5 degrees C) and high ECS (4.5 to 6.0 degrees C), and compares their post-1980 global average temperature simulation ranges to those of three surface temperature records and one satellite-based lower troposphere temperature data product.

Columns correspond to model groups showing low-ECS to high-ECS. Rows correspond to widely-used observed temperature records, the first three showing surface averages and the fourth showing the lower troposphere average. In each panel the yellow area denotes the mean and range ( $\pm$  one standard deviation) of climate model simulations for that group. The thick black line shows the observed annual average temperature in the indicated source.

Examination of the leftmost column shows that the low-ECS models track the post-1980 historical warming record reasonably well, but the middle and right columns show that the medium- and high-ECS models conspicuously over-predict the warming.



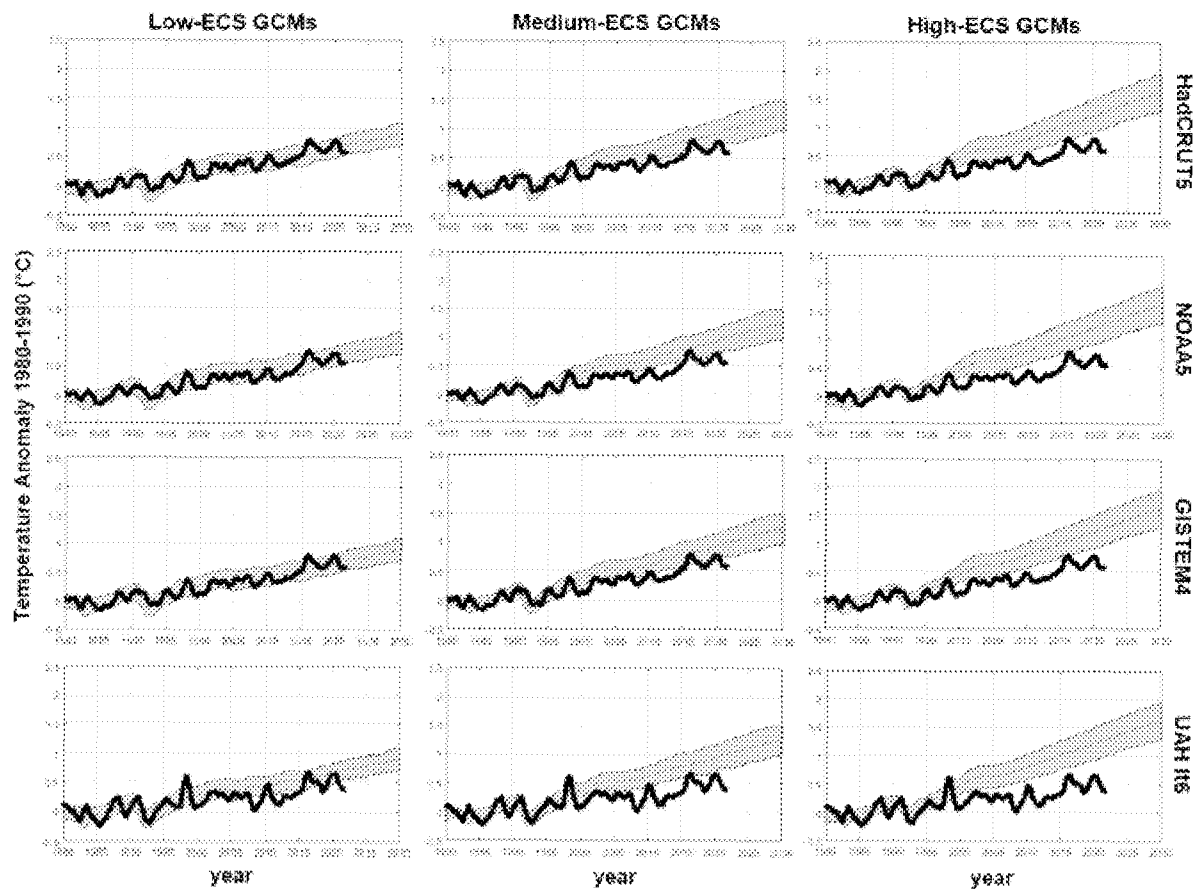
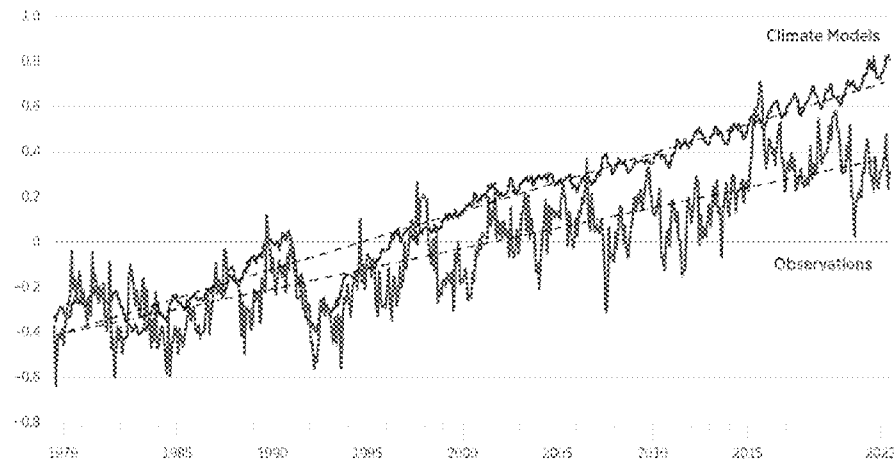


Figure 6.1: model-observational comparisons for Earth's surface warming. Source: Scafetta N. Climate Dynamics 2023 Fig.2. Rows: temperature data products as indicated. Columns: Low- to High-ECS models. Observations: black line. Model simulations: yellow band.

Spencer (2024) has also provided a useful summary of the Model-Observation mismatch by focusing on average surface temperature data products versus the average climate model warming, summarized in Figure 6.2.

### Global Average Surface-Air Temperature Variations, 1979~2022

DEPARTURE FROM 1951-2020 AVERAGE, 31 DEGREES CELSIUS



NOTE: Figures have been adjusted to align trends starting in 1979.

SOURCES: Authors' calculations based on data from five different observation-based datasets and 35 climate models taking part in the sixth IPCC Climate Model Intercomparison Project, and KNMI Climate Explorer, "Starting Point," <https://climate.knmi.nl/Start.asp> (accessed January 10, 2024).

Figure 6.2: Models versus observations at the surface. Source: Spencer (2024)

### 6.3. Tropospheric warming

It has long been known that climate models on average overstate warming in the troposphere over the tropics. Since this region generates the bulk of atmospheric warming in a GCM it is important to get the trends right. The discrepancy was flagged as a serious inconsistency in the first US Climate Change Science Program report (Karl et al. 2006) and has been mentioned in every IPCC report since, but it has gotten worse over time not better, and the bias is now global. McKittrick and Christy (2020) compare tropospheric warming rates in CMIP6 climate models to observations from satellites, weather balloons and reanalysis systems (Figure 6.3). Every single model overpredicts the observed warming trend in both Lower- and Mid-Troposphere layers, both globally and in the tropics (Figure 6.4).

In most individual cases the bias is statistically significant and on average it is highly significant. McKittrick and Christy (2020) also show that the bias is larger in high-ECS models, but even the models with lower average ECS predict too much warming. If a group of models were to appear that had a realistic representation of global tropospheric warming, it would likely have to have a lower ECS than even the low-ECS members of the CMIP6 ensemble

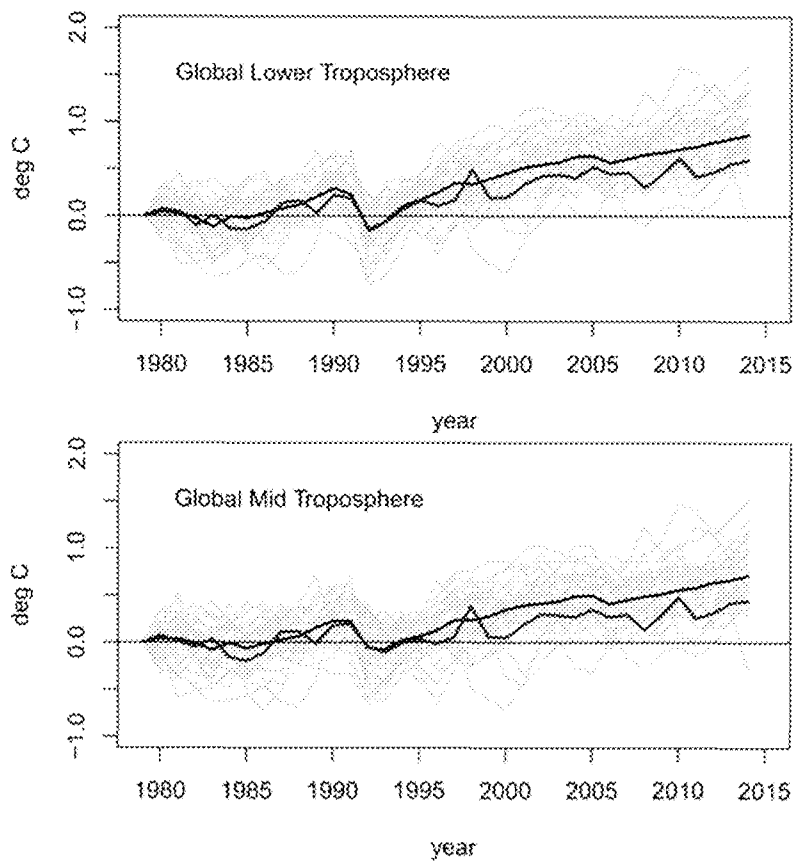


Figure 6.3: Models versus observations in the global troposphere. Source: McKittrick and Christy (2020). Gray lines: model runs. Black: average model run. Blue: average of satellite, radiosonde and reanalysis observations.

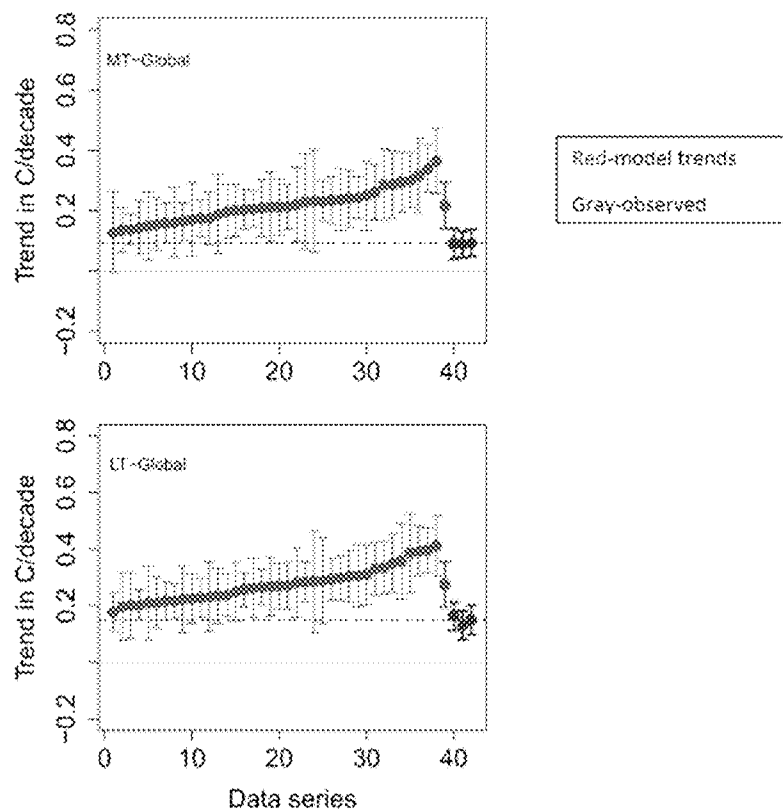


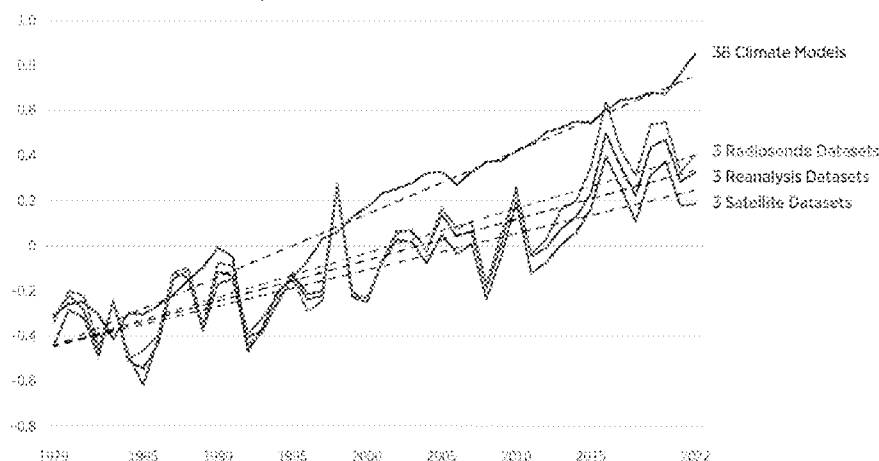
Figure 6.4: Modeled versus observed warming trends in the global troposphere. Adapted from McKittrick and Christy (2020). Red dots: model warming trend in  $^{\circ}\text{C}/\text{decade}$  with 95% confidence interval bars. Gray dots: observed warming trends in 3 data products (satellite, radiosondes and reanalysis) and 95% confidence interval bars.

Spencer (2024) shows the mismatch is also present in the lower troposphere:

CHART 3

## Global Lower Atmospheric Temperature Variations, 1979~2022

DEPARTURE FROM 1991-2020 AVERAGE, IN DEGREES CELSIUS



NOTE: Figures have been adjusted to align trends starting in 1979.

### SOURCES:

- Author's calculations based on data from Ross McKittrick and John Christy, "Persistent Warming Bias in CMIP6 Tropospheric Layers," *Earth and Space Science*, Vol. 7, No. 11 (Nov 14, 2020), <https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2020EF000128> (accessed January 10, 2023).
- Author's calculations based on data from American Meteorological Society, *State of the Climate in 2022*, <https://www.wamweather.gov/index.cfm/analysis/bulletin-of-the-american-meteorological-society-bulletin-of-the-climate/> (accessed January 9, 2023).

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Figure 6.5: Comparison of average trends in lower troposphere, 1979-2022. Source: Spencer (2024).

As mentioned the IPCC has long acknowledged the model-observational mismatch. The AR6 pp. 443-444 confirms model-observational mismatch in the troposphere the tropics (it does not address the global comparison):

Several studies since AR5 have continued to demonstrate an inconsistency between simulated and observed temperature trends in the tropical troposphere, with models simulating more warming than observations (Mitchell et al., 2013, 2020; Santer et al., 2017a, b; McKittrick and Christy, 2018; Po-Chedley et al., 2021)... Over the 1979–2014 period, models are more consistent with observations in the lower troposphere, and least consistent in the upper troposphere around 200 hPa, where biases exceed 0.1°C per decade. Several studies using CMIP6 models suggest that differences in climate sensitivity may be an important factor contributing to the discrepancy between the simulated and observed tropospheric temperature trends (McKittrick and Christy, 2020; Po-Chedley et al., 2021), though it is difficult to deconvolve the influence of climate sensitivity, changes in aerosol forcing and internal variability in contributing to tropospheric warming biases (Po-Chedley et al., 2021). Another study found that the absence of a hypothesized negative tropical cloud feedback could explain half of the upper troposphere warming bias in one model (Mauritsen and Stevens, 2015).

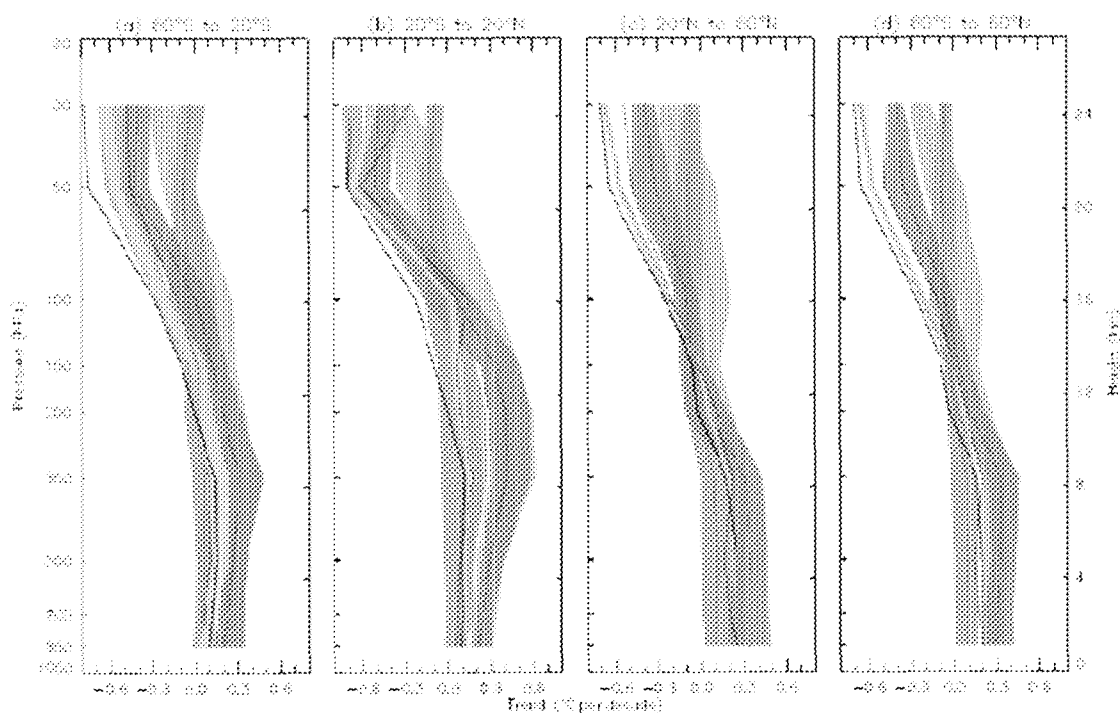
... In summary, studies continue to find that CMIP5 and CMIP6 model simulations warm more than observations in the tropical mid- and upper-troposphere over the 1979–2014 period (Mitchell et al., 2013, 2020; Santer et al., 2017a, b; Suárez-Gutiérrez et al., 2017; McKittrick and Christy, 2018), and that

overestimated surface warming is partially responsible (Mitchell et al., 2013; Po-Chedley et al., 2021). .... Hence, we assess with *medium confidence* that CMIP5 and CMIP6 models continue to overestimate observed warming in the upper tropical troposphere over the 1979–2014 period by at least 0.1°C per decade,

It is worth noting that despite the enormous accumulation of evidence of excess model warming the IPCC only assigns *medium confidence* to the existence of a warming bias. In other contexts they declare *high confidence* in phenomena established with much less evidence.

#### 6.4. Vertical profile mismatch and excess amplification

An important element of the model-observational discrepancy is the excess amplification with altitude found in climate models. A comparison was shown in the IPCC AR5 Chapter 10, although only in the online supplement. The diagram, reproduced below as Figure 6.6, compares temperature trends by altitude between models and observations, divided up into latitude bands.



**Figure 10.548.1** | Observed and simulated total mean temperature trends from 1979 to 2010 for CMIP5 simulations containing both anthropogenic and natural forcings (red), natural forcings only (blue) and greenhouse gas forcings only (green) where the 5th to 95th percentile ranges of the ensembles are shown. Three representative observations are shown (thick black line: Hadley Centre atmospheric temperature data set 2 (HadAT2), thin black line: Hadbourne (Interpolation of Interpolated using Mundaya (HadHC06)) 1.5, dark grey band: Hadbourne Interpolation Composite Homogenisation (HIC0-0.5, 1.5) ensemble and light grey: HIC0-0.5 + 1.5 ensemble. (Adapted from Jost et al. (2018) but for the more recent period from 1979 to 2010.)

10548-6

Figure 6.6: Vertical warming pattern by latitude band. Source: IPCC AR5 Figure 10.SM.1

The Figure is not referenced in the main report nor in any summary. What it shows, although it is not apparent at first glance, is that the 1979-2010 warming in the lower troposphere is so minimal it is consistent with models having no GHG forcing in them at all, and is inconsistent with the model runs that do have GHG forcing. Here is the main global band (60S to 60N) expanded with the observed trends highlighted in yellow:

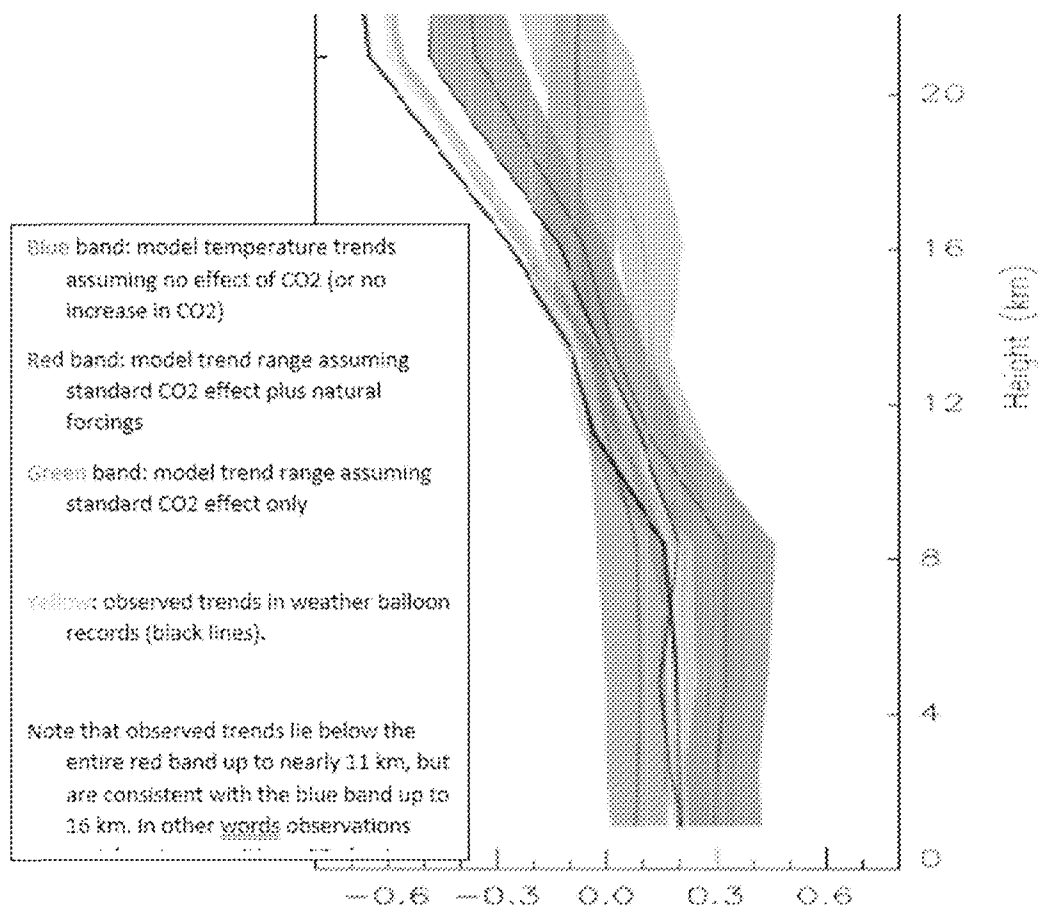


Figure 6.7: Adapted from IPCC AR5 Figure 10.SM.1

The next version of the Figure draws further detail out of the tropics band:

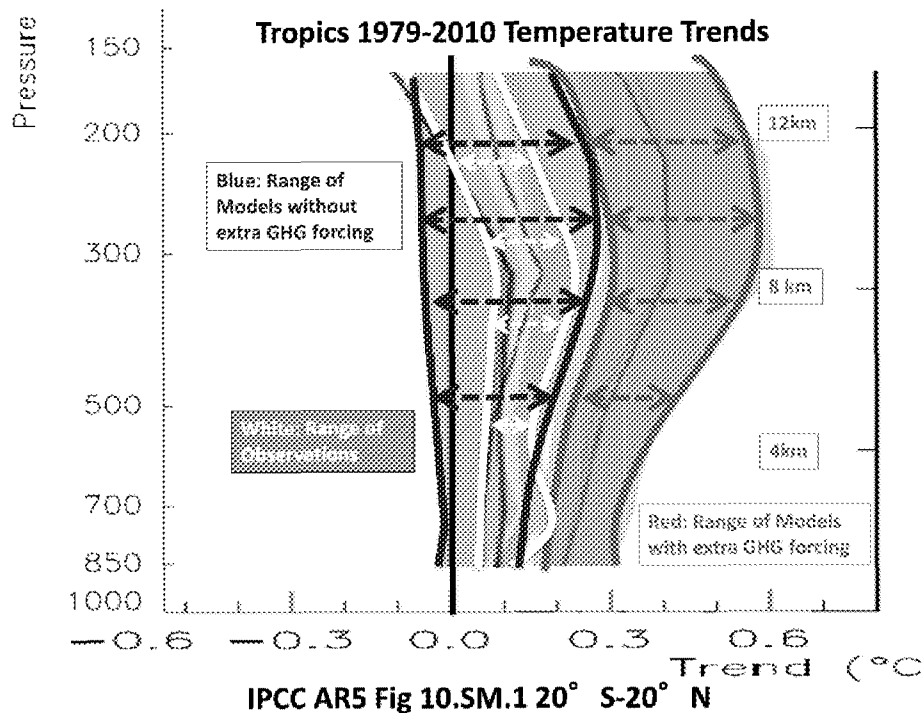


Figure 6.8: Adapted from IPCC AR5 Figure 10.SM.1.

In the tropics, where the models say the warming should be strongest, the observations (shown here in white) lie within the “No CO<sub>2</sub>” band and entirely outside the “with CO<sub>2</sub>” red envelope. This means that in the entire tropical atmospheric column from the surface to the stratosphere, *observed warming trends are so small they are consistent with the output of models that have no CO<sub>2</sub> warming effect in them, and they are inconsistent with the entire envelope of warming trends generated by models forced with increased CO<sub>2</sub>.*

A similar comparison is shown in Christy and McNider (2017), an updated version of which (covering 1979-2024) is reproduced as Figure 6.9. Modeled temperature trends exceed balloon observations from the surface through the top of the troposphere, with observed trends below the entire model range at most pressure levels. Also shown in Figure 6.9 is the TTT layer average from three satellite data products (NOAA, UAH and RSS) compared to the same layer average from climate models for 1979-2024. Again the observed trends lie below the entire model range.





## 6.5. Stratospheric cooling

An important element of the expected general “fingerprint” of anthropogenic climate change is simultaneous warming of the troposphere and cooling of the stratosphere. The IPCC AR6 acknowledged that cooling had been observed but only up to 2000. Thereafter the stratosphere has exhibited some warming, contrary to model projections.

The AR6 WG1 Ch 2 pp. 327-9 states (emphasis added):

“Temperatures averaged through the full lower stratosphere (roughly 10–25 km) have decreased over 1980–2019 in all data products, with the bulk of the decrease prior to 2000. The decrease holds even if the influence of the El Chichon (1982) and Pinatubo (1991) volcanic eruptions on the trend, found by Steiner et al. (2020a) to have increased the 1979–2018 cooling trend by 0.06°C per decade, is removed. **Most datasets show no significant or only marginally significant trends over 2000–2019, and the results of Philipona et al. (2018) show weak increases over 2000–2015** in the very lowermost stratosphere sampled by radiosondes....

It is virtually certain that the lower stratosphere has cooled since the mid-20th century. However, most datasets show that **lower stratospheric temperatures have stabilized since the mid-1990s with no significant change over the last 20 years**. It is likely that middle and upper stratospheric temperatures have decreased since 1980, but there is low confidence in the magnitude.

The cited source, Philipona et al. (2018), in an article entitled “Radiosondes Show That After Decades of Cooling, the Lower Stratosphere Is Now Warming”, stated:

“In response to continued greenhouse gas increases and stratospheric ozone depletion, climate models project continued tropospheric warming and stratospheric cooling over the coming decades. Global average satellite observations of lower stratospheric temperatures exhibit no significant trends since the turn of the century. In contrast, an analysis of vertically resolved radiosonde measurements from 60 stations shows an increase of lower stratospheric temperature since the turn of the century at altitudes between 15 and 30 km and over most continents. Trend estimates are somewhat sensitive to homogeneity assessment choices, but all investigated radiosonde data sets suggest a change from late twentieth century cooling to early 21st century warming in the lower stratosphere.”

## 6.6. Water vapour trends

Much of the warming in climate models derives not from GHG increases themselves but from water vapour feedbacks: extra warming induced by the projected accumulation of water vapour in the atmosphere after it warms due to CO<sub>2</sub>. But new evidence (Simpson et al. 2024) shows that models have over-projected increases in humidity.

“Water vapor in the atmosphere is expected to rise with warming because a warmer atmosphere can hold more moisture. However, over the last four decades, near-surface water vapor has not increased over arid and semi-arid regions. This is contrary to all climate model simulations in which it rises at a rate close to theoretical expectations, even over dry regions. This may indicate a major model misrepresentation of hydroclimate-related processes; models increase water vapor to satisfy the increased atmospheric demand, while this has not happened in reality.”

(Simpson et al. 2024)

While the models and observations matched over the 1988 to 2006 interval they diverge after that, directly contradicting model projections.

## 6.7. Snow cover

According to the Rutgers University Snow Lab (undated) the Northern Hemisphere winter snow cover shows an increasing trend over time.

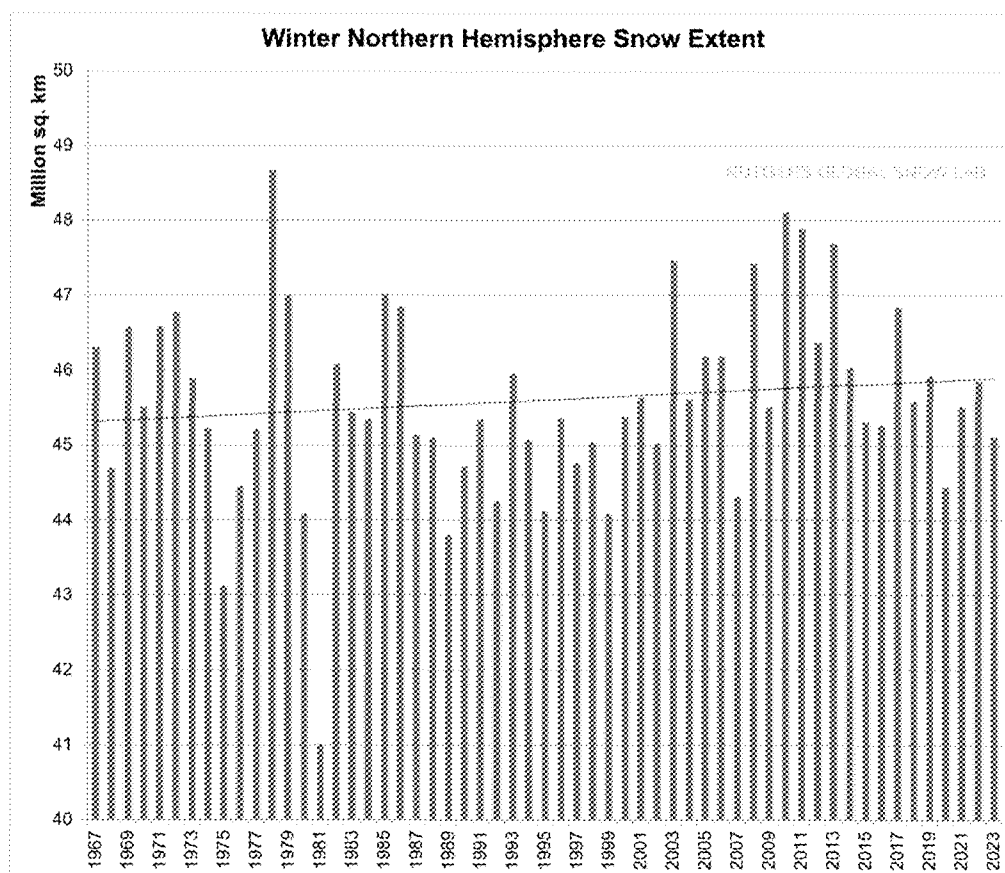


Figure 6.10: Northern Hemisphere Winter Snow extent. Source: [https://climate.rutgers.edu/snowcover/chart\\_seasonal.php?ui\\_set=nhl&ui\\_season=1](https://climate.rutgers.edu/snowcover/chart_seasonal.php?ui_set=nhl&ui_season=1) (February 24, 2024)

Models project declining Northern Hemisphere snow cover due to climate warming. But observations do not support this, as explained by Connolly et al. (2019).

Observed changes in Northern Hemisphere snow cover from satellite records were compared to those predicted by all available Coupled Model Intercomparison Project Phase 5 (“CMIP5”) climate models over the duration of the satellite’s records, i.e., 1967–2018. A total of 196 climate model runs were analyzed (taken from 24 climate models). Separate analyses were conducted for the annual averages and for each of the seasons (winter, spring, summer, and autumn/fall). A longer record (1922–2018) for the spring season which combines ground-based measurements with satellite measurements was also compared to the model outputs. **The climate models were found to poorly explain the observed trends. While the models suggest snow cover should have steadily decreased for all four seasons, only spring and summer exhibited a long-term decrease, and the pattern of the observed decreases for these seasons was quite different from the modelled predictions.** Moreover, the observed trends for autumn and winter suggest a long-term increase, although these trends were not statistically significant.

Connolly et al. (2019), emphasis added.

## 6.8. US Corn Belt

One of the largest discrepancies between models and observations can be found when we test them in a region of particular importance to global food production: the U.S. Corn Belt. Fig. 6.11 shows the warming trends for summertime (June, July, August) for the U.S. 12-state Corn Belt (IN, IA, NE, ND, SD, MO, MN, WI, MI, OH, KS, NE) during 1973-2022. All 36 climate models (red) produced too much warming compared to observations (blue) during 1973 to 2022.

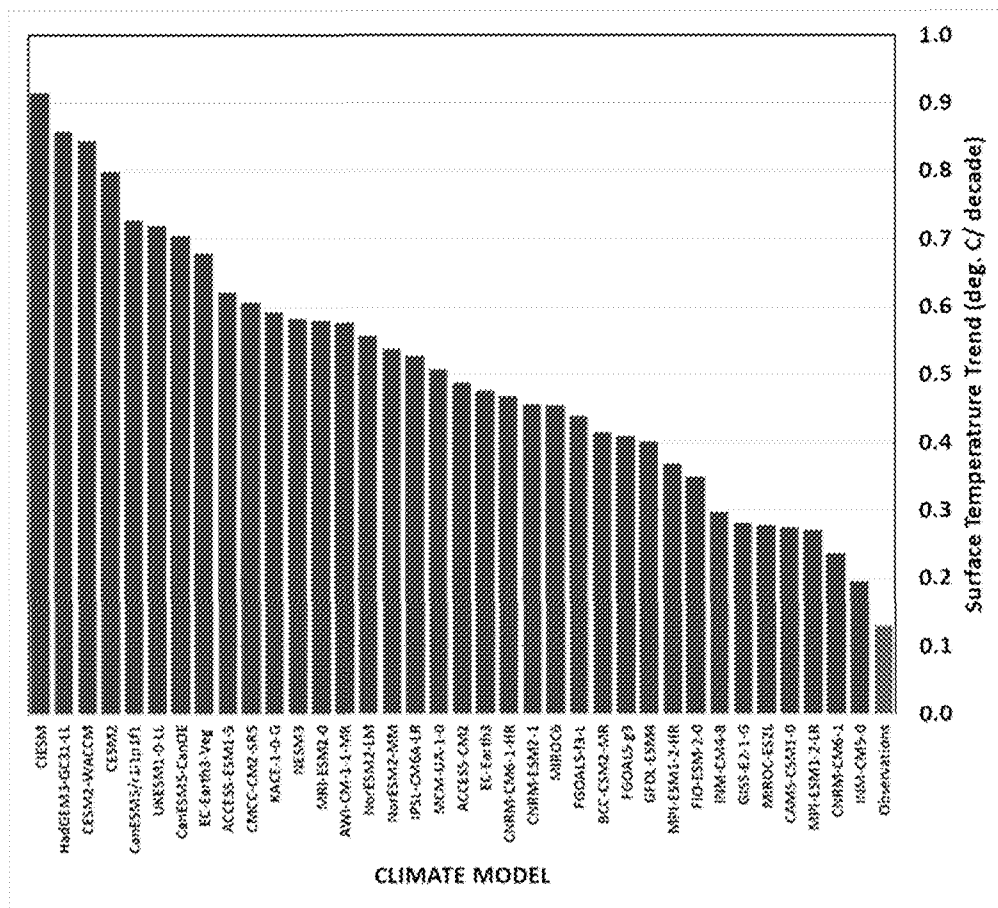


Figure 6.11: Modeled versus observed warming trends in the US corn belt.

As discussed in Chapter 10, the anticipated negative effects of increasing temperatures on U.S. corn yields have not materialized, which is in contrast to widely publicized studies proclaiming that theoretical future impacts are already being experienced (e.g. Seager et al., 2017).

Summarizing:

- Climate models show warming biases in many aspects of their reproduction of the past few decades.
- They produce too much warming at the surface (except in the models with lowest ECS), too much warming in the lower-and mid-troposphere and too much amplification of warming aloft
- They also produce too much stratospheric cooling, too much water vapor increase, too much snow loss, and too much warming in the corn belt.
- The IPCC has acknowledged some of these issues, buried the amplification problem and ignored others.

- The warm bias discussed here is consistent with independent evidence of model bias presented in Chapters 5 (measuring climate sensitivity) and 7 (optimal fingerprinting). Given the persistent warm bias in so many key aspects of climate model performance, users are justified in assuming that projections of future warming are also very likely to be biased too warm.

## 7. Uncertainties in Climate Change Attribution

### 7.1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) distinguishes between detection of climate change and attribution of cause. As defined by the IPCC AR6 WGI Glossary (IPCC, 2025):

*Detection:* "Detection of change is defined as the process of demonstrating that climate or a system affected by climate has changed in some defined statistical sense, without providing a reason for that change. An identified change is detected in observations if its likelihood of occurrence by chance due to internal variability alone is determined to be small, for example, <10%."

*Attribution:* "Attribution is defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with a formal assessment of confidence."

Both steps rely on statistical analysis. Detection focuses on whether changes are significant enough to stand out from random variation regardless of cause. Attribution involves comparison of observed events to model-generated counterfactuals. Since experimentation on the climate is not possible attribution requires statistical inference to assess how much human activities, such as GHG emissions, versus natural factors, like volcanic eruptions, explain observed changes. Attribution methods assume all external and internal drivers of the system are known and represented.

There are ongoing scientific debates around attribution methods, especially for attributing extreme weather events to climate change. The IPCC has long cautioned that methods to establish causality in climate science are inherently uncertain and ultimately depend on expert judgement. The Fourth Assessment Report: The Physical Science Basis (Hegerl et al., 2007) explained it as follows:

'Attribution' of causes of climate change is the process of establishing the most likely causes for the detected change with some defined level of confidence... unequivocal attribution would require controlled experimentation with the climate system. Since that is not possible, in practice attribution of anthropogenic climate change is understood to mean demonstration that a detected change is 'consistent with the estimated responses to the given combination of anthropogenic and natural forcing' and 'not consistent with alternative, physically plausible explanations of recent climate change that exclude important elements of the given combination of forcings' (IPCC, 2001)... The approaches used in detection and attribution research described above cannot fully account for all uncertainties, and thus ultimately expert judgement is required to give a calibrated assessment of whether a specific cause is responsible for a given climate change.

The Fifth Assessment Report Working Group II makes the following statement: (Cramer et al., 2014):

"Two broad challenges to the detection and attribution of climate change impacts relate to observations and process understanding. On the observational side, high-quality, long-term data relating to natural and human systems and the multiple factors affecting them are rare. In addition, the detection and

attribution of climate change impacts requires an understanding of the processes by which climate change, in conjunction with other factors, may affect the system in question.”

Because of the complexity of the causal chains in the climate system, investigation of these relationships is exceptionally challenging.

## 7.2 Attribution methods

The Intergovernmental Panel on Climate Change (IPCC) employs several attribution methods to assess the causes of observed climate changes, distinguishing between natural and human-induced factors. Below is a concise description of the key methods that have been used by the IPCC:

*Optimal Fingerprinting* uses linear regression to explain variations in observed climate data as a weighted sum of climate model simulations run with and without anthropogenic forcings. The data used in the regression model are weighted to try to minimize the influence of random noise and the estimation method is chosen to take account of climate model error.

*Time Series Analysis* exploits statistical differences between anthropogenic forcing and natural variability to see which one dominates observed temperatures, and also uses variations in the timing of changes to determine if causal dependence across data series can be inferred.

*Process-Based Attribution* focuses on understanding the physical mechanisms behind observed changes. This approach combines observations, climate models, and theoretical understanding to attribute changes in specific processes to forcings. This approach is often used for regional climate phenomena, such as monsoon changes or polar amplification

*Extreme Event Attribution* assesses in the role of human influence in the likelihood of occurrence or intensity of extreme weather events (e.g. heat waves, droughts). Methods include:

*Probabilistic Event Attribution* uses large ensembles of climate model simulations to compare observed events to model-generated counterfactuals

*Storyline Approach* examines the physical processes driving an event and evaluates how anthropogenic forcings may have modified those processes

## 7.3 Attribution of global warming

Attribution statements for global warming in the three most recent IPCC Assessment reports are:

AR4: “Most of the observed increase in global average temperatures since the mid-20<sup>th</sup> century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations.” (IPCC, 2007)

AR5: “It is *extremely likely* that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas



concentrations and other anthropogenic forcings together. The best estimate of the human- induced contribution to warming is similar to the observed warming over this period.” (IPCC, 2013)

AR6: “The *likely* range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019 is 0.8°C to 1.3°C, with a best estimate of 1.07°C. It is *likely* that well-mixed GHGs contributed a warming of 1.0°C to 2.0°C, other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C, natural drivers changed global surface temperature by –0.1°C to +0.1°C, and internal variability changed it by –0.2°C to +0.2°C. It is *very likely* that well-mixed GHGs were the main driver of tropospheric warming since 1979.” (IPCC, 2021)

The AR4 and AR5 attribution statements reference the warming since the mid-20<sup>th</sup> century, the period when greenhouse gas emissions began rapidly increasing. The words “most” and “more than half” are deliberately imprecise, potentially ranging from 51 to 99% of the warming – presumably this imprecision is to account for structural uncertainties such as natural internal variability. The confidence level increases from *very likely* to *extremely likely* from AR4 to AR5. The structure of the attribution statement in the AR6 is fundamentally different, referencing the warming to the period 1850-1900. The AR6 attribution statement is more precise numerically, but with a lower level of confidence at “likely” – the AR6 attributes essentially all of the warming to increases in greenhouse gases. The most confident statement from the AR6 relates to the tropospheric warming since 1979, using the words “main driver” and “*very likely*.”

There are three areas of substantive criticism of the IPCC assessment of the causes of the recent warming: inadequate assessment of natural climate variability, inappropriate statistical methods, and substantial discrepancies between models and observations. The latter is discussed in Chapter 7. The other two factors are discussed herein. Both of these issues are relevant not only in context of the main policy-relevant statement of the IPCC concerning attribution of the recent warming, but also because the global warming attribution provides the basis for extreme event attribution

## 7.2. Natural climate variability

The IPCC AR6 states that natural external drivers since 1850-1900 have changed global surface temperature by –0.1°C to +0.1°C, and internal variability has changed it by –0.2°C to +0.2°C – on average, having essentially no net impact on the warming since 1850-1900. This assessment of the contributions of natural variability has been disputed by a number of publications that question the magnitudes of the contributions from solar forcing and internal variability from the large-scale ocean circulations (R Connolly et al., 2021; W Soon, 2023).

If the Equilibrium Climate Sensitivity to CO<sub>2</sub> is low (Chapter 5), then natural climate variability becomes more important in the attribution of the recent warming. Further, if natural variability is higher, then estimates of the Equilibrium Climate Sensitivity from the historical period would be lower (Scafetta, 2023).

## Solar variability

The IPCC AR5 concluded that the best estimate of radiative forcing due to Total Solar Irradiance (TSI) changes for the period 1750–2011 was  $0.05 \text{ W/m}^2$  (Myrhe et al., 2014). The IPCC AR6 acknowledges a much larger range of estimates of changes in TSI over the last several centuries, stating that the TSI between the Maunder Minimum (1645–1715) and the second half of the twentieth century increased by  $0.7\text{--}2.7 \text{ W/m}^2$ , a range that includes both low and high variability TSI data sets (Gulev, 2021). However, the recommended forcing dataset for the CMIP6 climate model simulations used in the AR6 for attribution studies averages two data sets with low solar variability (Matthes, 2017).

While the IPCC AR6 shows a substantially greater solar impact than does the AR5, the overall impact on the climate was assessed to be small compared to anthropogenic forcing of climate change. However, the impact of solar variations on the climate is uncertain and subject to substantial debate – something that you would not infer from the IPCC assessment reports (Lockwood, 2012; Connolly et al., 2021).

Exactly how TSI has changed over time has been a challenging problem to resolve. Since 1978, there have been direct measurements of TSI from satellites. However, the data exhibit non-negligible inconsistencies, and interpreting any multi-decadal trends in TSI requires comparisons of observations from overlapping satellites. There are several rival composite TSI datasets, disagreeing as to whether TSI increased or decreased during the period 1986–96 (the ACRIM gap; see Chapter 4). Further, the satellite record of TSI is used for calibrating proxy models, whereby past solar variations are inferred from sunspots and cosmogenic isotope measurements (Velasco Herrera et al., 2015).

There is substantial evidence for high solar activity in the second half of the 20<sup>th</sup> century (starting in 1959) and extending into the 1990's, before a decline in the early 21<sup>st</sup> century; this period is often termed the “Modern Maximum.” (Chatzistergos et al., 2023; Solanki et al., 2004; Usoskin et al., 2007). However, some scientists have concluded that it is not possible to be confident of any multi-decadal trend in TSI (Schmutz, 2021).

As a result of this uncertainty, some reconstructions for past values of TSI (since 1750) have low variability, implying a very low impact of solar variations on global mean surface temperature, whereas datasets with high TSI variability can explain more than 70% percent of the temperature variability since preindustrial times (Scafetta, 2013; Stefani, 2021). Hence, the choice of which TSI satellite record used in an analysis can substantially influence how much climate change is attributed to human versus natural forcings.

There is growing evidence that other aspects of solar variability, which are referred to as solar indirect effects, amplify TSI forcing or are independent of TSI forcing. Scafetta et al. (2023) suggests that ~80% of solar influence on climate may stem from non-TSI mechanisms. Candidate processes include: solar ultraviolet changes; energetic particle precipitation; atmospheric-electric-field effect on cloud cover; cloud changes produced by solar-modulated galactic cosmic rays; large relative changes in the magnetic field; and the strength of the solar wind. Solar indirect effects are not included in climate models, although indirect methods of estimating these effects suggest significant influence. However, claims of non-TSI mechanisms influencing climate are uncertain and debated.

## Natural variability of large-scale ocean circulations

Variations in global mean surface temperature are linked to recurrent large-scale variations in ocean circulation patterns. These circulation patterns include the Atlantic Multidecadal Oscillation (AMO), the Pacific Decadal Oscillation (PDO) and the El Niño-Southern Oscillation (ENSO). These circulation patterns influence ocean heat uptake and heat distribution, and also influence atmospheric circulation patterns and cloud distributions. There is some debate as to whether these variations are strictly internal to the climate system, or whether this variability can have a solar/astronomical origin or can be influenced by large volcanic eruptions.

While climate models simulate the large-scale ocean circulations and internal climate variability, the simulated magnitude in the multi-decadal band is too low in most models relative to observations, and the phasing of the variability in long-term climate simulations is not synced with the actual, observed climate variations (Kravtsov et al. 2024). Averaging multiple simulations from climate models effectively averages out the internal variations, leaving only the forced climate variability (e.g., CO<sub>2</sub> forcing). With most of the modern warming beginning in the late 1970's, the recent 50-year warming is on the same time scale as the multi-decadal oscillations of the AMO and PDO.

Here are summary statements from the IPCC AR5 and AR6 reports:

"Decadal variability in the Pacific, associated with the PDO or IPO, contributes significantly to regional and global temperature trends, but the relative contributions of internal variability and external forcing are difficult to disentangle in CMIP5 simulations." (IPCC, 2013)

"Since AR5, there has been increased understanding of the role of internal variability, such as ENSO, PDO, and AMO, in modulating regional climate trends. However, limitations in simulating the exact timing and amplitude of these modes in CMIP6 models contribute to uncertainties in attributing observed changes to anthropogenic forcing (high confidence)." (IPCC, 2021)

The amplitude of the peak-to-trough impact of the multi-decadal oscillations on global temperatures has been assessed by the IPCC AR6: "The likely range of change due to internal variability is -0.2°C to +0.2°C (IPCC, 2021)." This implies a trough-to-peak change of 0.4°C. Over many centuries, any global temperature changes from the troughs and peaks will cancel out, with little to no net impact.

However, with a nominal timescale of 60-80 years for oscillations such as the AMO and PDO, the timing of the peaks and troughs can be confused with the secular trend. This becomes very relevant for attributing the warming for the 50 years since 1975, during which most of the warming has occurred. Even if climate models have the correct amplitude of the multidecadal oscillations, the timing of the peaks and troughs is not adequately simulated, with each model and individual ensemble simulating a different phasing. Once the simulations of the ensemble members and different models are averaged, the natural internal variability contribution is averaged out, effectively cancelling the role of natural internal variability in the attribution process.

The Great Pacific Climate Shift of 1976-1977 was a notable climatic event characterized by an abrupt change in the North Pacific Ocean's atmosphere-ocean system that interacted with global climate

patterns. This shift is closely associated with the Pacific Decadal Oscillation (PDO) that oscillates between warm and cool phases over decades. The 1976 shift marked a transition from a predominantly negative (cool) PDO phase (1947–1976) to a positive (warm) phase (1977 through 2000), with significant implications for global and regional climate patterns including the frequencies of El Niño and La Niña events. The Great Pacific Climate Shift coincided with the beginning of a period of accelerated global warming (REF TO A FIG OF GLOBAL TEMP ANOMALIES ELSEWHERE IN DOC) When the Great Pacific Climate Shift is accounted for in climate attribution analyses since 1950, it has been found that 40 percent or more of the warming in the second half of the 20<sup>th</sup> century was caused by natural internal variability (McLean et al., 2009; Tung and Zhou, 2013; Chylek et al., 2016; Scafetta, 2021).

### 7.3. Optimal fingerprinting

Optimal fingerprinting is a statistical technique introduced by Allen and Tett (1999) that compares observed climate data to climate model simulations to identify patterns (or "fingerprints") associated with human or natural forcing. It involves taking a vector of observed climate changes, such as warming rates in locations around the world, and decomposing them into a weighted sum of "signals", which are analogues to the observations generated by climate models with different types of forcings. The weights are chosen using a regression method called Total Least Squares. The analysis commonly uses just two signals, one generated by models using only anthropogenic forcings and one using only natural forcings. If the estimated weighting coefficient attached to a signal is significantly different from zero, then that signal is said to be "detected". If it is close to 1.0, then the model generating the signal is said to be consistent with observations. If it is less than 1.0, then the model signal for that forcing is too strong and needs to be scaled down, and vice-versa. Both the observed data and the signals are weighted using a model-generated estimate of patterns of randomness in the climate system so as, in principle, to put maximum weight on regions where natural variability is minimized.

Optimal fingerprinting is the primary tool for attribution in the climate literature. Studies applying it have been cited thousands of times, and it has been prominently featured by the IPCC since the 2001 Third Assessment Report. One of its inherent weaknesses is that results depend on assumptions about the accuracy of climate models, especially regarding their representation of natural variability (IPCC AR5 Ch 10.2.3).

Additionally, a series of papers by McKittrick (McKittrick 2022a, 2022b, 2023, 2025) has challenged the optimal fingerprinting method, arguing that it is inherently unreliable and that commonly used practices in econometrics can provide more valid results. Statistical theory requires that for regression models to yield unbiased coefficients, a set of assumptions called the Gauss-Markov conditions must hold. McKittrick (2022a) argued that the Allen and Tett (1999) methodology violates the Gauss-Markov conditions, leading to potentially biased and inconsistent fingerprinting coefficients, undermining the reliability of the method. Chen et al. (2023) confirmed this analysis and argued that the method could yield unbiased results but only under very stringent assumptions. McKittrick (2022b) and (2023) raised a further concern that climate scientists—virtually alone among scientific disciplines—have used an estimation method called Total Least Squares (TLS) to estimate anthropogenic greenhouse gas signal coefficients, despite its tendency to be unreliable unless some strong assumptions hold that in practice are unlikely to be true. Under conditions which easily arise in optimal fingerprinting, TLS yields estimates with large

positive biases. Thus, any study that has used TLS for optimal fingerprinting without verifying that it is appropriate in the specific data context has likely overstated the result.

McKittrick (2025) presented an empirical example comparing the results of conventional optimal fingerprinting against methods drawn from mainstream econometrics which are known to be valid for the specific application of signal detection. While the IPCC optimal fingerprinting method yields an anthropogenic signal coefficient close to 1.0 on a global temperature data set spanning 1900 to 2010, consistent estimation yields a coefficient around 0.4, which rises to about 0.65 on data spanning 1980 to 2010, implying the model response to greenhouse gases needs to be scaled down by about half to optimally match observations. The natural forcing signal coefficient, by contrast, is between 2.0 and 4.0, implying the climate model signals of natural forcing need to be scaled up two-to four-fold to match observed climate change. The fingerprinting coefficients estimated in McKittrick (2025), when used to scale the average sensitivity of the climate models used to generate the forcing signals in his data set, imply a Transient Climate Sensitivity of 1.4°C, which matches the estimate by Lewis (2022) using a different estimation method and multiple independent data sets.

While these analyses do not prove that all of the results from using the IPCC optimal fingerprinting method are wrong, it does show that the basis on which they were believed to be correct is non-existent – hence reducing confidence in the results.

#### **7.4. Time series methods**

The IPCC (AR5 WGI 10.2.2) drew attention to alternative approaches of assessing causality that emerged from the time series econometrics literature. They have the advantage of not depending on assumptions about the accuracy of climate models, but their disadvantage is they depend on assumptions about the data generating process underlying climate and forcing data that are not straightforward to test. The methods, now referred to as climate econometrics, use the tools of unit root testing, Granger causality and cointegration analysis, all of which are familiar in economics and finance and which are slowly being adopted in climate science. Time series analysis methods hold out the possibility of determining whether anthropogenic or natural forcings are the primary drivers of climate change without requiring the use of climate models, although key questions remain unsettled (e.g. Dergiades et al. 2016, Balcombe et al. 2019, Dagsvik et al. 2020, Razzak 2022, Dagsvik and Moen 2023).

Granger causality modeling is a tool for determining directions of influence in data series that move together. “Granger causality” is a statistical, not a physical, concept. If knowing the current value of one variable significantly improves the forecast accuracy of another variable we can infer a causal connection exists; this is called Granger causality. The modeling tools, called vector autoregression, measure direct impulse-response patterns and feedbacks. An application to the well-known Vostok ice core data revealed an error by Al Gore in his documentary *An Inconvenient Truth*. Gore showed the data and drew attention to the coherence of temperature and CO<sub>2</sub> changes over a 440,000 year span, which he asserted was due to CO<sub>2</sub> driving temperature changes. But temperature changes can also affect atmospheric CO<sub>2</sub> levels. Davidson et al. (2015) examined the series and found that temperature Granger causes CO<sub>2</sub> but not the reverse. In other words on the time scales represented in the Vostok data the coherence in the

series is primarily due to the influence of temperature on CO<sub>2</sub> levels not the feedback going from CO<sub>2</sub> to temperature.

In summary, the main statistical methods for attributing causation in climate data are optimal fingerprinting and time series analysis. Applications of the Allen and Tett (1999) optimal fingerprinting method dominate the attribution literature and have underpinned past IPCC conclusions, but results depend on the accuracy of climate models and the method has recently been criticized as inherently biased. Time series methods do not depend on climate models but require assumptions of their own and have generated results that have thus far not converged on a consensus.

## **7.5. Extreme event attribution (EEA)**

The IPCC AR6 provides an ambiguous assessment of the role of global warming in the historical record of extreme weather and climate events. Chapter 11 of WG1 states (Seneviratne et al., 2021):

“Evidence of observed changes in extremes and their attribution to human influence (including greenhouse gas and aerosol emissions and land-use changes) has strengthened since AR5, in particular for extreme precipitation, droughts, tropical cyclones and compound extremes (including dry/hot events and fire weather). Some recent hot extreme events would have been extremely unlikely to occur without human influence on the climate system.”

By contrast, Chapter 12 of WG1 (Table12.12) paints a different picture – presumably, the expert judgment of different groups of authors for the two chapters came to different conclusions (Ranasinghe, 2021):

*High confidence* in an increase in extreme heat events in tropical regions where observations allow trend estimation and in most regions in the mid-latitudes, medium confidence elsewhere

*Medium confidence* in a decrease in extreme cold events in Australia, Africa and most of northern South America where observations allow trend estimation

No evidence of emergence in the historical period of a change in river floods, heavy precipitation, drought, fire weather, severe wind storms, and tropical cyclones

While the overall issue of detecting changes in extreme weather events and their attribution remains ambiguous, most of the activity in this area relates to the attribution of single extreme weather events. The most prominent effort is the World Weather Attribution (WWA; [worldweatherattribution.org](http://worldweatherattribution.org)), which is an international research initiative that focuses on extreme event attribution analyzing how climate change influences the likelihood and intensity of extreme weather events. The approach used by the WWA runs large ensembles of regional climate models to compare the event in today’s climate, versus a pre-industrial counterfactual climate without human-caused warming.

WWA plays a prominent role in linking extreme weather to climate change and its press releases attract considerable public and policy discussions. However, the WWA’s tendency to promote non-peer-

reviewed findings, funding ties, open admission that they shape their analyses to serve purposes of litigation and other methodological challenges have sparked controversies, with critics questioning the robustness and impartiality of its conclusions (Pielke Jr. 2024). Despite these issues, WWA's work continues to shape climate science and media narratives. Technical criticisms of the approach include: neglect of a formal detection process; an implicit assumption that 100% of the post-industrial warming is caused by CO<sub>2</sub>; and failure to adequately account for natural internal climate variability.

Because EEA is relatively new many basic methodological issues have yet to be settled in the expert literature. An important challenge is the lack of data. Extreme events are by definition rare. Many analyses of extreme event types (including the US National Assessment Reports) only evaluate data since 1950 or 1970. However, as emphasized by Chapter 8, many of the worst extreme weather and climate events in U.S. history occurred prior to the first half of the 20<sup>th</sup> century including in the early 19<sup>th</sup> century. And if paleoclimate reconstructions are considered, it becomes very difficult for an event to pass the detection thresholds of exceeding what is expected from natural variability, particularly if a reasonably sized geographic region is considered.

Another challenge is defining the event under study. There is a longstanding literature in statistics and econometrics on the challenge of analyzing data with outliers. The issue arises because a data series establishes a probability distribution defining the expected range of observations. If an outlier is observed it might indicate that the underlying process giving rise to the data distribution has changed (which in the weather context would mean a climatic change has been detected) or that the underlying process has multiple regimes each with a different probability distribution, in which case observing an outlier simply means we were temporarily in a different regime, but the system itself was unchanged. If a time series contains only a single outlier event at the end of the series it is not possible to determine which model is the correct one (Chen and Liu 1993). For instance, there might be an "ordinary" weather regime that yields a distribution of summer daytime highs in a particular coastal region, and a second "heatwave" regime that kicks in when an inland blocking event occurs, which yields a temperature distribution centered 15°C higher than the first one. A day with temperatures 13°C above normal would either be an extreme heat anomaly under the first regime or a somewhat cool event under the second, and we have no way in this case of knowing on statistical grounds which view is correct.

Visser and Petersen (2012) and Sardeshmukh et al. (2015) both point out that different distributions may fit observed data equally well but yield very different implications about the likelihood of a specific weather event. Visser and Petersen argue that, in view of the deep uncertainties of extreme weather analysis drawing a connection between individual events and global climate change should be avoided. Furthermore the existence of an outlier at the end of a data series poses the problem that estimates of the event probabilities will be biased whether the outlier is included or excluded (Barlow et al. 2020). Methods to eliminate the bias have not yet been established, leading some experts (e.g. Miralles and Davison 2023) to argue that in settings in which a data series contains a single extreme event at the end, estimation of a return period for the extreme event will be so biased and uncertain it should be avoided altogether.

In spite of these concerns, the U.S. is presently considering something like the WWA, which is being investigated by a NASEM Panel on Attribution of Extreme Weather and Climate Events and their impacts (NASEM, 2025).

A case studies from a recent high impact extreme events in the U.S. is provided to illustrate the challenges and ambiguities in attributing the frequency and intensity of extreme weather events to human-caused warming.

## **7.6. Case study – 2021 Western North America heat wave**

The 2021 Western North America heat wave was an extreme heat wave that affected much of Western North America in late June 2021. In particular, surface temperature records were set in Portland, OR (116°F; previous record 107°F) and Seattle, WA (108 °F; previous record 103°F) (Mass et al., 2024).

The WWA team garnered international headlines for their analysis and provided the following attribution statements (WWA, 2021; Philip et al., 2022):

Based on observations and modeling, the occurrence of this heatwave was virtually impossible without human-caused climate change.

The event is estimated to be about a 1 in 1000-year event in today's climate.

The event would have been at least 150 times rarer without human-induced climate change.

This heatwave was about 2°C hotter than it would have been if it had occurred at the beginning of the industrial revolution (when global mean temperatures were 1.2°C cooler than today).

But an important caveat to the first claim is that other researchers concluded, based on historical weather data, that while a heat wave of the magnitude observed was indeed virtually impossible without anthropogenic climate change, it was also virtually impossible *with* climate change. Bercos-Hickey (2022) noted “these temperatures were virtually impossible under any previously experienced meteorological conditions, with or without global warming.” McKinnon and Simpson (2022) stated “the most likely explanation remains that the weather event itself was ‘bad luck.’” The 2023 Oregon Climate Assessment (Fleischman 2023) concluded that the heat dome would have formed even without climate change and “There is no evidence that the highly unusual combination of weather features that drove the heat dome were made more likely by climate change, and climate models do not project an increase in the frequency of high-pressure ridges over the Pacific Northwest” (Fleischman 2023 p. 49).

Mass et al. (2024) summarizes the proximate sequence of compound events leading to the heat wave. There was a record-breaking midtropospheric ridge over the Pacific Northwest, forced by a tropical disturbance in the western Pacific. This produced record-breaking midtropospheric temperatures, strong subsidence in the lower atmosphere, low-level easterly flow that produced downslope warming on regional terrain and the removal of cooler marine air, and an approaching low-level trough that enhanced downslope flow. The event occurred at a time of maximum solar insolation, and drier-than-normal soil moisture. Using a storyline approach, Mass et al. assessed that there is no trend in drought and dry soils in the Pacific Northwest; there is no evidence of global warming producing stronger ridges of high pressure, and no observed trend in heat waves or record temperatures in the region. They



concluded that although anthropogenic warming may have contributed as much as 2°F to the magnitude of the event, there is little evidence of further amplification of the event from increasing greenhouse gases.

A statistical analysis of a model-based attribution study of this heat wave was conducted by Bercos-Hickey et al. (2022). Because this event is a far outlier and far above the bounds of Generalized Extreme Value distributions fitted from historical data, they concluded that estimates of return times, quantitative changes in event magnitude and frequency, and probability of the extreme temperatures such as provided by the WWA are not accurate and should be interpreted as having low confidence. They found that hindcast attribution methods using an ensemble of regional climate models, combined with Pearl (2009) causal inferences, can provide limited and conditional information about the magnitude of the human influence on this heatwave – they provided a more highly constrained estimate that human activities caused a ~1.4°C–1.8°F increase in the daily maximum temperatures.

Zeder et al. (2023) also concluded that the methods employed by Philip et al. (2022) tend to overstate the rarity of extreme heat waves, leading to a biased perception of the effect of climate change on the heatwave event: “The tendency to overestimate the return period of observed extreme heatwave events may fuel the impression that seemingly impossible heatwave extremes are currently clustering at an unprecedented rate.”

The 2021 Western North America heatwave was a rare and unprecedented compound weather event, that broke century-old temperature records by as much as 9°F. While the WWA team received worldwide publicity for their rapid attribution claims blaming anthropogenic climate change, subsequent peer-reviewed analysis showed that the rare event was not made more probable by global warming.

## **7.7. Summary**

There is an ongoing scientific debate around attribution methods, particularly in attributing extreme weather events to climate change. The IPCC has long cautioned that methods to establish causality in climate science are inherently uncertain and ultimately depend on expert judgement.

There are two areas of substantive criticism of the IPCC assessment of the causes of the recent warming: inadequate assessment of natural climate variability, and inappropriate statistical methods.

Detection of extreme weather events is challenged by their rarity, requiring a long data set and a choice of region and spatial scale to evaluate their occurrence against the background of natural weather and climate variability.

The most robust attribution statements for an extreme event relate to an incremental change (e.g. a temperature change in degrees or percent change in rainfall). Statements related to return times,

quantitative changes in event magnitude and frequency, and probability of the extremes are not accurate owing to an inadequate amount of data, and are made with low confidence. There is no evidence in a change of weather or climate regime patterns from increasing greenhouse gases that would amplify or dampen extreme weather events, beyond basic thermodynamic considerations.

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## 8. Extreme weather in the US and elsewhere

### 8.1. Introduction

Weather extremes, usually related to temperature and/or precipitation, can disrupt infrastructure and therefore endanger human health and wellbeing. The issue is not whether extremes occur, for they are intrinsic to the chaotic climate system. Rather, it is whether there are long-term (decadal scale) changes in the frequency or character of extremes (“detection”), as well as the extent to which such changes and the attendant changes in hazards are caused by anthropogenic emissions of greenhouse gases (“attribution”; e.g., IPCC AR6 Seneviratne et al. 2021).

It is naïve to assume that any recent unprecedented extreme event is caused by human influences on the climate. That assumption is wrong in two ways. First, climate is about the statistical properties of weather over decades, not single events. And second, there are only about 130 years of reliable observational records that can be analyzed statistically. That brief interval does not begin to contain all of the extreme events that the climate system can create on its own. Over geologic time the climate system has generated an (essentially) infinite variety of weather patterns and extremes that humans have never observed, and thus are absent from the databases used to determine extreme statistics.<sup>3</sup> [see *Perils of short data records* below]. For that reason, attributing an extreme event unprecedented in the record requires assumptions about the magnitude of natural variations.

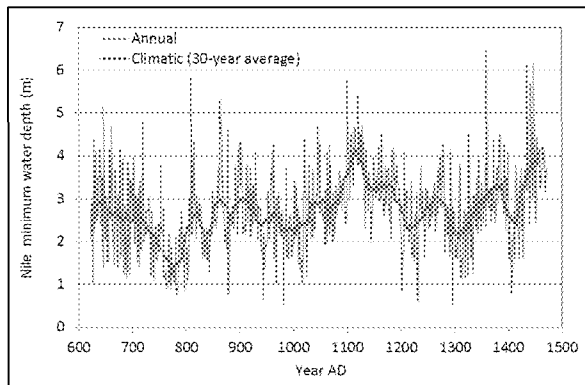
This is especially true for precipitation events. The hydrological literature has long noted the phenomenon of *Long Term Persistence* (LTP) in rainfall data (Hurst 1951, Cohn and Lins 2005, Markonis and Koutsoyiannis 2015). LTP has a formal mathematical definition but it can be thought of intuitively as the presence of natural variations with strong autocorrelation properties that result in cycle-like behavior on long time scales. The presence of LTP requires long records to accurately estimate variability. Analysis of records short relative to the LTP scale will tend to underestimate variability, therefore overstating the significance of apparent trends and underestimating the likelihood of extreme events (Cohn and Lins 2005).

A good example of LTP is the eight-century long record of the annual minimum height of the Nile River observed at Roda Island in Cairo shown below in Figure 8.1.1. Since human influences on the global climate were negligible before the 20<sup>th</sup> century, the century-scale variability of the thirty-year average is entirely natural; Egyptians of the seventh and eight centuries would have been incorrect to assume that the worsening drought during that time was the “new normal.”

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<sup>3</sup> For example, under the simplest statistical assumptions there is a 37 percent chance that a 100-year event is NOT present in a century-long record.





**Figure 8.1.1:** Nile River discharge [details, source]

With these caveats in mind we examine the evidence for changes in selected weather and climate extremes. It has become routine in media discussions, government and private sector discussions and even in some academic literature to make generalized assertions that extreme weather of all types is getting worse due to GHGs and climate change. Yet expert assessments have not typically drawn such sweeping conclusions and instead have emphasized the difficulty both of identifying specific trends and establishing a causal connection with anthropogenic forcing. For the benefit of readers who may not have read the relevant reports we will begin with extended excerpts of findings from previous IPCC and NCA assessments, then in the remainder of this chapter survey additional data relevant to US and global extreme weather trends.

## 8.2. Review of IPCC and NCA Findings on Extreme Weather

The sources we review will be denoted as follows:

**SREX:** The IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (2012)

**AR5:** The IPCC Fifth Assessment Report Working Group 1 (2013).

**AR6:** The IPCC Sixth Assessment Report Working Group 1 (2021).

**NCA17:** The US Climate Science Special Report of the Fourth National Climate Assessment (2017) Volume I Chapter 6.

### 8.2.1 Overview: IPCC Assessment of signal emergence in extreme weather types

(AR6 WG1 Table 12.12)

| Climate Impact Driver Type | Climate Impact Driver Category         | Already Emerged in the Historical Record? | Emerging by 2050 in Most Extreme CO2 Emissions Scenario? | Emerging by 2100 in Most Extreme CO2 Emissions Scenario? |
|----------------------------|----------------------------------------|-------------------------------------------|----------------------------------------------------------|----------------------------------------------------------|
| Heat & Cold                | Average air temperature                | YES in most regions                       | YES                                                      | YES                                                      |
|                            | More heat extremes                     | YES in most regions                       | YES in land regions                                      | YES                                                      |
|                            | Fewer cold extremes                    | YES in a few regions                      | YES in many regions                                      | YES                                                      |
|                            | Less frost                             | NO                                        | NO                                                       | NO                                                       |
| Wet & Dry                  | Average Precip. (Increase or Decrease) | NO                                        | YES (incr) YES (decr)                                    | YES (incr) YES (decr)                                    |
|                            | River flooding                         | NO                                        | NO                                                       | NO                                                       |
|                            | Heavy precip & pluvial flood           | NO                                        | NO                                                       | YES in a few regions                                     |
|                            | Landslide                              | NO                                        | NO                                                       | NO                                                       |
|                            | Aridity                                | NO                                        | NO                                                       | NO                                                       |
|                            | Hydrologic Drought                     | NO                                        | NO                                                       | NO                                                       |
|                            | Agricultural & ecological drought      | NO                                        | NO                                                       | NO                                                       |
|                            | Fire weather                           | NO                                        | NO                                                       | NO                                                       |
| Wind                       | Average wind speed                     | NO                                        | NO                                                       | NO                                                       |
|                            | Severe wind storm                      | NO                                        | NO                                                       | NO                                                       |
|                            | Tropical cyclone                       | NO                                        | NO                                                       | NO                                                       |
|                            | Sand and dust storm                    | NO                                        | NO                                                       | NO                                                       |
| Snow and Ice               | Snow, glacier & ice sheet              | NO                                        | YES in a few regions                                     | YES Arctic snow                                          |
|                            | Permafrost                             | YES                                       | YES                                                      | YES                                                      |
|                            | Lake & river ice                       | NO                                        | YES                                                      | YES                                                      |
|                            | Arctic sea ice                         | YES                                       | YES                                                      | YES                                                      |
|                            | Antarctic sea ice                      | NO                                        | YES                                                      | YES                                                      |

|            |                                  |                          |     |     |
|------------|----------------------------------|--------------------------|-----|-----|
|            | Heavy snowfall and ice storm     | NO                       | NO  | NO  |
|            | Hail                             | NO                       | NO  | NO  |
|            | Snow avalanche                   | NO                       | NO  | NO  |
| Coastal    | Relative sea level               | NO                       | YES | YES |
|            | Coastal flood                    | NO                       | NO  | NO  |
|            | Coastal erosion                  | NO                       | NO  | NO  |
| Open Ocean | Average ocean temperature        | YES                      | YES | YES |
|            | Marine heat wave                 | NO                       | NO  | NO  |
|            | Ocean acidity                    | NO                       | YES | YES |
|            | Ocean salinity                   | YES                      | YES | YES |
|            | Dissolved oxygen                 | YES (Pacific & S. Ocean) | YES | YES |
| Other      | Air pollution weather            | NO                       | NO  | NO  |
|            | Solar or IR radiation at surface | NO                       | NO  | NO  |

**Table 8.2.1.** IPCC AR6 summary of the probable emergence of an anthropogenic signal above natural climate variability for all global or regional “climate impact drivers” (CIDs) of concern for humans and ecosystems in response to increasing atmospheric greenhouse gas concentrations (primarily CO<sub>2</sub>). Source: Table adapted from report of Working Group I, Table 12.12). Red = high confidence; yellow = medium confidence; green = no anthropogenic signal detectable above natural variability (50% confidence).

Table 8.2.1 reproduces the findings of AR6 Table 12.12 which indicates, for 34 major weather event and impact types, whether a signal of anthropogenic forcing has been detected in the historical record (column 1), whether such a signal is likely to emerge by 2050 under the extreme RCP8.5 scenario (column 2) and whether it is likely to emerge by 2100 under RCP8.5 forcing (column 3). It should be borne in mind that the latter two columns suffer from the deficiencies of GCMs discussed in Chapter XX. And as we discussed in Ch X on attribution, AR6 offers conflicting messages about attribution of extreme weather. Nevertheless, we provide this Table for reference.

Several patterns stand out. First, detection of an anthropogenic signal is asserted with *high confidence* in only four of the 34 weather impact categories, and with *medium confidence* in a further four. The IPCC

does NOT claim to have detected an anthropogenic signal in the remaining 26 categories. Of the four *high confidence* assertions, two are for changes in average temperatures (air and ocean), which are not measures of extreme weather. Further, two of the four *medium confidence* assertions are related to ocean chemistry and also not related to extreme weather. The IPCC does NOT assert a detectable human influence on many non-temperature weather features such as wind, precipitation, flooding, and drought.

Second, columns 2 and 3 show that the IPCC expects very few anthropogenic trends to emerge within this century, *even under the most extreme forcing scenario*. As we discuss in Section 4.2 the RCP8.5 scenario is an implausible high-end storyline, not a “base case” or “business-as-usual” projection. Even so, most weather impacts are not expected to show an anthropogenic signal this century. Natural variability dominates patterns of extreme weather systems and simplistic assertions of trend detection are frequently undermined by regional heterogeneity and trend reversals over time.

Taking wind as an example, the IPCC claims that an anthropogenic signal has NOT emerged in average wind speeds, severe windstorms, tropical cyclones, or sand and dust storms, and none are expected to emerge this century even under an extreme emissions scenario. The same applies to drought and fire weather. This table alone suffices to illustrate the gap between IPCC expert assessments of extreme weather and discussions in the popular media and political arenas. As we show below the Table reflects longstanding conclusions of the IPCC and other assessment bodies. In the next few sections we will simply present without comment excerpts from past assessment reports.<sup>4</sup> In selecting these excerpts, we’ve focused on the highest-level summaries to avoid accusations of bias through “cherry picking”.

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<sup>4</sup> In these excerpts we have added **bold-face** emphasis, while *italicized* emphasis on confidence terms appears in the original sources. Citations in quoted text can be found in the underlying reports but are not reproduced here.

## 8.2.2 Flooding

SREX (p. 176)

In the United States and Canada during the 20th century and in the early 21st century, there is no compelling evidence for climate-driven changes in the magnitude or frequency of floods.

AR5 (p. 214)

AR4 WGI Chapter 3 (Trenberth et al., 2007) did not assess changes in floods but AR4 WGII concluded that **there was not a general global trend in the incidence of floods** (Kundzewicz et al., 2007). SREX went further to suggest that there was low agreement and thus *low confidence* at the global scale regarding changes in the magnitude or frequency of floods or even the sign of changes.

AR5 WGII assesses floods in regional detail accounting for the fact that trends in floods are strongly influenced by changes in river management (see also Section 2.5.2). Although the most evident flood trends appear to be in northern high latitudes, where observed warming trends have been largest, in some regions no evidence of a trend in extreme flooding has been found, for example, over Russia based on daily river discharge (Shiklomanov et al., 2007). Other studies for Europe (Hannaford and Marsh, 2008; Renard et al., 2008; Petrow and Merz, 2009; Stahl et al., 2010) and Asia (Jiang et al., 2008; Delgado et al., 2010) show evidence for upward, downward or no trend in the magnitude and frequency of floods, so that there is currently no clear and widespread evidence for observed changes in flooding except for the earlier spring flow in snow-dominated regions (Seneviratne et al., 2012).

In summary, there continues to be a lack of evidence and thus *low confidence* regarding the sign of trend in the magnitude and/or frequency of floods on a global scale.

AR6 (Ch 11 p. 1568)

The SREX (Seneviratne et al., 2012) assessed *low confidence* for observed changes in the magnitude or frequency of floods at the global scale. This assessment was confirmed by the AR5 report (Hartmann et al., 2013). The SR15 (Hoegh-Guldberg et al., 2018) found increases in flood frequency and extreme streamflow in some regions, but decreases in other regions. **While the number of studies on flood trends has increased since the AR5 report, and there were also new analyses after the release of SR15 (Berghuijs et al., 2017; Blöschl et al., 2019; Gudmundsson et al., 2019), hydrological literature on observed flood changes is heterogeneous, focusing at regional and sub-regional basin scales, making it difficult to synthesise at the global and sometimes regional scales.**

In summary, the seasonality of floods has changed in cold regions where snowmelt dominates the flow regime in response to warming (*high confidence*). **Confidence about peak flow trends over past decades on the global scale is *low*, but there are regions experiencing increases**, including parts of Asia,

southern South America, the northeast USA, northwestern Europe, and the Amazon, **and regions experiencing decreases**, including parts of the Mediterranean, Australia, Africa, and the southwestern USA.

US NCA17 pp. 240-41:

“The IPCC AR5 did not attribute changes in flooding to anthropogenic influence nor report detectable changes in flooding magnitude, duration, or frequency. Trends in extreme high values of streamflow are mixed across the United States. Analysis of 200 U.S. stream gauges indicates areas of both increasing and decreasing flooding magnitude but does not provide robust evidence that these trends are attributable to human influences...

The complex mix of processes complicates the formal attribution of observed flooding trends to anthropogenic climate change and suggests that additional scientific rigor is needed in flood attribution studies. As noted above, precipitation increases have been found to strongly influence changes in flood statistics. However, in U.S. regions, **no formal attribution of precipitation changes to anthropogenic forcing has been made so far, so indirect attribution of flooding changes is not possible. Hence, no formal attribution of observed flooding changes to anthropogenic forcing has been claimed.**”

### 8.2.3 Heatwaves

AR5 (p. 212 WG1)

Table 2.13 shows that there has been a *likely* increasing trend in the frequency of heatwaves since the middle of the 20th century in Europe and Australia and across much of Asia where there are sufficient data. However, confidence on a global scale is *medium* owing to lack of studies over Africa and South America but also in part owing to differences in trends depending on how heatwaves are defined (Perkins et al., 2012). Using monthly means as a proxy for heatwaves Coumou et al. (2013) and Hansen et al. (2012) indicate that record-breaking temperatures in recent decades substantially exceed what would be expected by chance but caution is required when making inferences between these studies and those that deal with multi-day events and/ or use more complex definitions for heatwave events. **There is also evidence in some regions that periods prior to the 1950s had more heatwaves (e.g., over the USA, the decade of the 1930s stands out and is also associated with extreme drought conditions** (Peterson et al., 2013) whereas conversely in other regions heatwave trends may have been underestimated owing to poor quality and/or consistency of data (e.g., Della-Marta et al. (2007a) over Western Europe; Kuglitsch et al. (2009, 2010) over the Mediterranean). Recent available studies also suggest that the number of cold spells has reduced significantly since the 1950s (Donat et al., 2013a, 2013c).

In summary, new analyses continue to support the AR4 and SREX conclusions that since about 1950 it is *very likely* that the numbers of cold days and nights have decreased and the numbers of warm days and

nights have increased overall on the global scale, that is, for land areas with sufficient data. It is *likely* that such changes have also occurred across most of North America, Europe, Asia and Australia.

NCA17 (pp. 190-191)

Changes in warm extremes are more nuanced than changes in cold extremes. For instance, the warmest daily temperature of the year increased in some parts of the West over the past century (Figure 6.3), but there were decreases in almost all locations east of the Rocky Mountains. In fact, all eastern regions experienced a net decrease (Table 6.2), most notably the Midwest (about 2.2°F [1.2°C]) and the Southeast (roughly 1.5°F [0.8°C]). The decreases in the eastern half of [the] Nation, particularly in the Great Plains, are mainly tied to the unprecedented summer heat of the 1930s Dust Bowl era, which was exacerbated by land-surface feedbacks driven by springtime precipitation deficits and land mismanagement. However, anthropogenic aerosol forcing may also have reduced summer temperatures in the Northeast and Southeast from the early 1950s to the mid-1970s, and agricultural intensification may have suppressed the hottest extremes in the Midwest.

Since the mid-1960s, there has been only a very slight increase in the warmest daily temperature of the year (amidst large interannual variability). **Heat waves (6-day periods with a maximum temperature above the 90th percentile for 1961–1990) increased in frequency until the mid-1930s, became considerably less common through the mid-1960s, and increased in frequency again thereafter (Figure 6.4). As with warm daily temperatures, heat wave magnitude reached a maximum in the 1930s.**

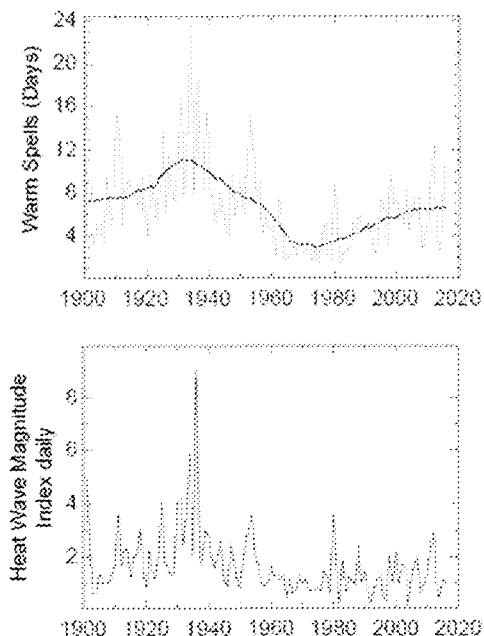


Figure 8.2.1: US Heat waves since 1900. Source: NCA17 Figure 6.4

AR6 (p. 1550)

In North America (Table 11.19), there is very robust evidence for a *very likely* increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes for the whole continent, though there are substantial spatial and seasonal variations in the trends. Minimum temperatures display warming consistently across the continent, **while there are more contrasting trends in the annual maximum daily temperatures** in parts of the USA (Figure 11.9; Lee et al., 2014; van Oldenborgh et al., 2019; Dunn et al., 2020).

#### 8.2.4 Extreme snowfall events

Note: extreme snowfall events in the US northeast are assessed in relation to winter Extratropical Cyclone (ETC) activity.

AR6 Ch 11. p. 1593

There is *high confidence* that snowfall associated with winter ETCs will decrease in the future, because increases in tropospheric temperatures lead to a lower proportion of precipitation falling as snow (O’Gorman, 2014; Rhoades et al., 2018; Zarzycki, 2018). However, there is *medium confidence* that extreme snowfall events associated with winter ETCs will change little in regions where snowfall will be supported in the future (O’Gorman, 2014; Zarzycki, 2018).

#### 8.2.5 Extreme precipitation

SREX (p. 142)

Recent studies have updated the assessment of the AR4, with more regional results now available (Table 3-2). Overall, this additional evidence confirms that **more locations and studies show an increase than a decrease in extreme precipitation, but that there are also wide regional and seasonal variations**, and trends in many regions are not statistically significant (Table 3-2)... Based on station data from Canada, the United States, and Mexico, Peterson et al. (2008a) reported that heavy precipitation has been increasing over 1950-2004, as well as the average amount of precipitation falling on days with precipitation.

AR5 (pp. 213-14)

In summary, further analyses continue to support the AR4 and SREX conclusions that it is *likely* that since 1951 there have been statistically significant increases in the number of heavy precipitation events (e.g., above the 95th percentile) in more regions than there have been statistically significant decreases, but



there are strong regional and subregional variations in the trends. In particular, many regions present statistically non-significant or negative trends, and, where seasonal changes have been assessed, there are also variations between seasons (e.g., more consistent trends in winter than in summer in Europe). The overall most consistent trends towards heavier precipitation events are found in central North America (very likely increase) but assessment for Europe shows likely increases in more regions than decreases.

AR6 (p. 1560)

In North America, there is robust evidence that the magnitude and intensity of extreme precipitation has *very likely* increased since the 1950s. Both [one-day maxima] and [5-day maxima] have significantly increased in North America during 1950-2018 (Sun et al., 2020, also Figure 11.13). There is, however, regional diversity. In Canada, there is a lack of detectable trends in observed annual maximum daily (or shorter duration) precipitation (Shephard et al., 2014; Mekis et al., 2015; Vincent et al., 2018).

NCA17 pp. 213-14:

Detectability of trends (compared to internal variability) for a number of precipitation metrics over the continental United States has been examined; **however, trends identified for the U.S. regions have not been clearly attributed to anthropogenic forcing.** One study concluded that increasing precipitation trends in some north-central U.S. regions and the extreme annual anomalies there in 2013 were at least partly attributable to the combination of anthropogenic and natural forcing... **Based on current evidence, it is concluded that detectable but not attributable increases in mean precipitation have occurred over parts of the central United States.** Formal detection-attribution studies indicate a human contribution to extreme precipitation increases over the continental United States, but confidence is *low* based on those studies alone due to the short observational period, high natural variability, and model uncertainty.

In summary, based on available studies, it is concluded that for the continental United States there is *high confidence* in the detection of extreme precipitation increases, while there is *low confidence* in attributing the extreme precipitation changes purely to anthropogenic forcing.

#### 8.2.6 Tornadoes and severe convective storms

IPCC AR6 Sct. 11.7.3, p. 1594

Severe convective storms are convective systems that are associated with extreme phenomena such as tornadoes, hail, heavy precipitation (rain or snow), strong winds, and lightning.

The assessment of changes in severe convective storms in SREX (Chapter 3, Seneviratne et al., 2012) and AR5 (Chapter 12, Collins et al., 2013) is limited and focused mainly on tornadoes and hail storms. The

SREX assessed that **there is *low confidence* in observed trends in tornadoes and hail** because of data inhomogeneities and inadequacies in monitoring systems. Subsequent literature assessed in the Climate Science Special Report (Kossin et al., 2017) led to the assessment of the observed tornado activity over the 2000s in the USA, with a decrease in the number of days per year with tornadoes and an increase in the number of tornadoes on these days (*medium confidence*). However, **there is *low confidence* in past trends for hail and severe thunderstorm winds**. Climate models consistently project environmental changes that would support an increase in the frequency and intensity of severe thunderstorms that combine tornadoes, hail, and winds (*high confidence*), but there is *low confidence* in the details of the projected increase.

... In summary, because the definition of severe convective storms varies depending on the literature and the region, it is not straightforward to make a synthesizing view of observed trends in severe convective storms in different regions. In particular, **observational trends in tornadoes, hail, and lightning associated with severe convective storms are not robustly detected** due to insufficient coverage of the long-term observations. There is *medium confidence* that the mean annual number of tornadoes in the USA has remained relatively constant, but their variability of occurrence has increased since the 1970s, particularly over the 2000s, with **a decrease in the number of days per year, and an increase in the number of tornadoes on these days** (*high confidence*). Detected tornadoes have also increased in Europe, but the trend depends on the density of observations.

... In summary, **it is extremely difficult to detect and attribute changes in severe convective storms**. There is limited evidence that extreme precipitation associated with severe convective storms has increased in some cases.

#### 8.2.7 Hurricanes and Tropical Cyclones

SREX (p. 159):

There have been no significant trends observed in global tropical cyclone frequency records, including over the present 40-year period of satellite observations (e.g., Webster et al., 2005). Regional trends in tropical cyclone frequency have been identified in the North Atlantic, but the fidelity of these trends is debated (Holland and Webster, 2007; Landsea, 2007; Mann et al., 2007a). Different methods for estimating undercounts in the earlier part of the North Atlantic tropical cyclone record provide mixed conclusions (Chang and Guo, 2007; Mann et al., 2007b; Kunkel et al., 2008; Vecchi and Knutson, 2008). Regional trends have not been detected in other oceans (Chan and Xu, 2009; Kubota and Chan, 2009; Callaghan and Power, 2011). It thus remains uncertain whether any observed increases in tropical cyclone frequency on time scales longer than about 40 years are robust, after accounting for past changes in observing capabilities (Knutson et al., 2010).

AR5 (pp. 216-17):

**Current data sets indicate no significant observed trends in global tropical cyclone frequency** over the past century and it remains uncertain whether any reported long-term increases in tropical cyclone frequency are robust, after accounting for past changes in observing capabilities (Knutson et al., 2010). **No robust trends in annual numbers of tropical storms, hurricanes and major hurricanes counts have been identified** over the past 100 years in the North Atlantic basin. Measures of land-falling tropical cyclone frequency (Figure 2.34) are generally considered to be more reliable than counts of all storms which tend to be strongly influenced by those that are weak and/or short lived. Callaghan and Power (2011) find a statistically significant decrease in Eastern Australia land-falling tropical cyclones since the late 19th century although including 2010/2011 season data this trend becomes non-significant (i.e., a trend of zero lies just inside the 90% confidence interval). Significant trends are not found in other oceans on shorter time scales (Chan and Xu, 2009; Kubota and Chan, 2009; Mohapatra et al., 2011; Weinkle et al., 2012), although Grinsted et al. (2012) find a significant positive trend in eastern USA using tide-gauge data from 1923–2008 as a proxy for storm surges associated with land-falling hurricanes. Differences between tropical cyclone studies highlight the challenges that still lie ahead in assessing long-term trends.

In summary, this assessment does not revise the SREX conclusion of *low confidence* that any reported long-term (centennial) increases in tropical cyclone activity are robust, after accounting for past changes in observing capabilities. More recent assessments indicate that **it is unlikely that annual numbers of tropical storms, hurricanes and major hurricanes counts have increased over the past 100 years in the North Atlantic basin**. Evidence, however, is for a virtually certain increase in the frequency and intensity of the strongest tropical cyclones since the 1970s in that region.

AR6 (p. 1585)

There is *low confidence* in most reported long-term (multidecadal to centennial) trends in TC frequency- or intensity-based metrics due to changes in the technology used to collect the best-track data. This should not be interpreted as implying that no physical (real) trends exist, but rather as indicating that either the quality or the temporal length of the data is not adequate to provide robust trend detection statements, particularly in the presence of multidecadal variability.

There are previous and ongoing efforts to homogenize the best-track data (Elsner et al., 2008; Kossin et al., 2013, 2020; Choy et al., 2015; Landsea, 2015; Emanuel et al., 2018) and there is substantial literature that finds positive trends in intensity-related metrics in the best-track during the “satellite period”, which is generally limited to the past ~40 years (Kang and Elsner, 2012; Kishtawal et al., 2012; Kossin et al., 2013, 2020; Mei and Xie, 2016; Zhao et al., 2018; Tauvale and Tsuboki, 2019). **When best-track trends are tested using homogenized data, the intensity trends generally remain positive, but are smaller in amplitude** (Kossin et al., 2013; Holland and Bruyère, 2014). **Kossin et al. (2020) extended the homogenized TC intensity record to the period 1979–2017 and identified significant global increases in major TC exceedance probability of about 6% per decade.**<sup>5</sup> In addition to trends in TC intensity, there is

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<sup>5</sup> The **underlined** text referenced a study (Kossin et al. 2020) that later retracted a portion of its findings. Those authors assembled a data set on global TC incidence spanning 1979 to 2017 from which they claimed that the global fraction of TCs reaching major status (Cat 3–5) rose from 27% during 1979-1997

evidence that TC intensification rates and the frequency of rapid intensification events have increased within the satellite era (Kishtawal et al. 2012; Balaguru et al., 2018; Bhatia et al., 2018). The increase in intensification rates is found in the best-track as well as the homogenized intensity data.

A subset of the best-track data corresponding to hurricanes that have directly impacted the United States since 1900 is considered to be reliable, and shows no trend in the frequency of U.S. landfall events (Knutson et al., 2019).

#### 8.2.8 Droughts

**US NCA17 REPORT** (Ch. 8, Wehner et al. 2017)

p. 231:

Recent droughts and associated heat waves have reached record intensity in some regions of the United States; however, by geographical scale and duration, the Dust Bowl era of the 1930s remains the benchmark drought and extreme heat event in the historical record (very high confidence). **While by some measures drought has decreased over much of the continental United States in association with long-term increases in precipitation, neither the precipitation increases nor inferred drought decreases have been confidently attributed to anthropogenic forcing.**

The human effect on recent major U.S. droughts is complicated. Little evidence is found for a human influence on observed precipitation deficits, but much evidence is found for a human influence on surface soil moisture deficits due to increased evapotranspiration caused by higher temperatures. (*High confidence*)

p. 233:

Drought is, of course, directly connected to seasonal precipitation totals. Figure 7.1 shows detectable observed recent changes in seasonal precipitation. In fact, the increases in observed summer and fall precipitation are at odds with the projections in Figure 7.5. **As a consequence of this increased precipitation, drought statistics over the entire CONUS have declined.**

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to 31% during 1998-2017 and that the increase was statistically significant. However, closer examination of their results showed a significant increase only in the North Atlantic (18% to 34%) whereas changes in all other basins (Eastern Pacific, Western Pacific, North Indian, South Indian, South Pacific) were not statistically significant. In a subsequent correction (<https://www.pnas.org/doi/10.1073/pnas.2021573117>), Kossin et al. stated that the global probability of observing a major TC rose from 34% during 1979-1997 to 37% in the later period and that the evidence for statistical significance was now weaker. Nevertheless, the authors claimed that the correction did not affect their conclusions.

SREX (p. 170)

From a paleoclimate perspective recent droughts are not unprecedented, with severe ‘megadroughts’ reported in the paleoclimatic record for Europe, North America, and Australia (Jansen et al., 2007). Recent studies extend this observation to African and Indian droughts (Sinha et al., 2007; Shanahan et al., 2009): much more severe and longer droughts occurred in the past centuries with widespread ecological, political, and socioeconomic consequences. Overall, these studies confirm that in the last millennium several extreme droughts have occurred (Breda and Badeau, 2008; Kallis, 2008; Büntgen et al., 2010).

**In North America, there is *medium confidence* that there has been an overall slight tendency toward less dryness** (wetting trend with more soil moisture and runoff; Table 3-2), although analyses for some subregions also indicate tendencies toward increasing dryness. This assessment is based on several lines of evidence, including simulations with different hydrological models as well as PDSI and CDD estimates (Alexander et al., 2006; Andreadis and Lettenmaier, 2006; van der Schrier et al., 2006a; Kunkel et al., 2008; Sheffield and Wood, 2008a; Dai, 2011).

**The most severe droughts in the 20th century have occurred in the 1930s and 1950s**, where the 1930s Dust Bowl was most intense and the 1950s drought most persistent (Andreadis et al., 2005) in the United States, while in Mexico the 1950s and late 1990s were the driest periods. Recent regional trends toward more severe drought conditions were identified over southern and western Canada, Alaska, and Mexico, with subregional exceptions (Dai, 2011).

SREX (p. 172)

Overall, though new studies have furthered the understanding of the mechanisms leading to drought, there is still relatively limited evidence to provide an attribution of observed changes, in particular given the issues associated with the availability of observational data (Section 3.2.1) and the definition and computation of drought indicators (Box 3-3). This latter point was mostly identified in post-AR4 studies (Box 3-3). Moreover, regions where consistent increases in drought are identified (see ‘Observed Changes’) are only partly consistent with those where projections indicate an enhancement of drought conditions in coming decades (see next paragraphs). We thus assess that there is *medium confidence* (see also Section 3.1.5) that anthropogenic influence has contributed to some changes in the drought patterns observed in the second half of the 20<sup>th</sup> century, based on its attributed impact on precipitation and temperature changes (though temperature can only be indirectly related to drought trends; see Box 3-3). However there is *low confidence* in the attribution of changes in droughts at the level of individual regions.

AR5 (pp. 214-215)

Based on evidence since AR4, SREX concluded that there were not enough direct observations of dryness to suggest high confidence in observed trends globally, although there was *medium confidence* that since the 1950s some regions of the world have experienced more intense and longer droughts. The

differences between AR4 and SREX are due primarily to analyses post-AR4, differences in how both assessments considered drought and updated IPCC uncertainty guidance.

Because drought is a complex variable and can at best be incompletely represented by commonly used drought indices, discrepancies in the interpretation of changes can result. For example, Sheffield and Wood (2008) found decreasing trends in the duration, intensity and severity of drought globally. Conversely, Dai (2011a,b) found a general global increase in drought, although with substantial regional variation and individual events dominating trend signatures in some regions (e.g., the 1970s prolonged Sahel drought and the 1930s drought in the USA and Canadian Prairies). Studies subsequent to these continue to provide somewhat different conclusions on trends in global droughts and/or dryness since the middle of the 20th century (Sheffield et al., 2012; Dai, 2013; Donat et al., 2013c; van der Schrier et al., 2013).

In summary, the current assessment concludes that there is not enough evidence at present to suggest more than *low confidence* in a global-scale observed trend in drought or dryness (lack of rainfall) since the middle of the 20th century, owing to lack of direct observations, geographical inconsistencies in the trends, and dependencies of inferred trends on the index choice. Based on updated studies, AR4 conclusions regarding global increasing trends in drought since the 1970s were probably overstated. However, it is *likely* that the frequency and intensity of drought has increased in the Mediterranean and West Africa and decreased in central North America and north-west Australia since 1950.

AR6 (Drought, Observed trends, Section 11.6.2, pp. 1573-75)

p. 1573

Strong precipitation deficits have been recorded in recent decades in the Amazon (2005, 2010), south-western China (2009–2010), south-western North America (2011–2014), Australia (1997–2009), California (2014), the middle East (2012–2016), Chile (2010–2015), the Great Horn of Africa (2011), among others (van Dijk et al., 2013; Mann and Gleick, 2015; Rowell et al., 2015; Marengo and Espinoza, 2016; Dai and Zhao, 2017; Garreaud et al., 2017, 2020; Marengo et al., 2017; Brito et al., 2018; Cook et al., 2018). **Global studies generally show no significant trends in SPI time series** (Orlowsky and Seneviratne, 2013; Spinoni et al., 2014), **and in derived drought frequency and severity data** (Spinoni et al., 2019), with very few regional exceptions (Section 11.9 and Figure 11.17).

p. 1574

For AR6 regions, several studies suggest an increase in the frequency and areal extent of soil moisture deficits, with examples in East Asia (Cheng et al., 2015; Y. Qin et al., 2015; Jia et al., 2018), Western and Central Europe (Trnka et al., 2015b), and the Mediterranean (Hanel et al., 2018; Moravec et al., 2019; Markonis et al., 2021). **Nonetheless, some analyses also show no long-term trends in soil drying in**

some AR6 regions – for example, in Eastern North America (Park Williams et al., 2017) and Central North America (Seager et al., 2019), as well as in North Eastern Africa (Kew et al., 2021).

There is evidence based on streamflow records of increased hydrological droughts in East Asia (D. Zhang et al., 2018) and southern Africa (Gudmundsson et al., 2019). **In areas of Western and Central Europe and Northern Europe, there is no evidence of changes in the severity of hydrological droughts since 1950** based on flow reconstructions (Caillouet et al., 2017; Barker et al., 2019) and observations (Vicente-Serrano et al., 2019). **In North America, depending on the methods, datasets and study periods, there are differences between studies that suggest an increase (Shukla et al., 2015; Udall and Overpeck, 2017) versus a decrease in hydrological drought frequency (Mo and Lettenmaier, 2018), but in general there is strong spatial variability** (Poshtiri and Pal, 2016). Streamflow observation reference networks of near-natural catchments have also been used to isolate the effect of climate trends on hydrological drought trends in a few regions, but these show limited trends in Northern Europe and Western and Central Europe (Stahl et al., 2010; Bard et al., 2015; Harrigan et al., 2018), North America (Dudley et al., 2020) and most of Australia, with the exception of Eastern and Southern Australia (X.S. Zhang et al., 2016).

p. 1575

**Few AR6 regions show observed increases in meteorological drought** (Section 11.9), mostly in Africa and South America (NES: *high confidence*; WAF, CAF, ESAF, SAM, SWS, SSA, SAS: *medium confidence*); a few others show a decrease (WSB, ESB, NAU, CAU, NEU, CNA: *medium confidence*). There are stronger signals indicating observed increases in agricultural and ecological drought (Section 11.9), which highlights the role of increased [evapotranspiration], driven by increased [Atmospheric Evaporative Demand], for these trends (Sections 11.6.2.3, 11.6.2.5). Past increases in agricultural and ecological droughts are found on all continents and several regions (WAF, CAF, WSAF, ESAF, WCA, ECA, EAS, SAU, MED, WCE, NES: *medium confidence*), while decreases are found only in one AR6 region (NAU: *medium confidence*). The more limited availability of datasets makes it more difficult to assess historical trends in hydrological drought at regional scale (Section 11.9). Increasing (MED: *high confidence*; WAF, EAS, SAU: *medium confidence*) and decreasing (NEU, SES: *medium confidence*) trends in hydrological droughts have only been observed in a few regions.

AR6 on Attribution (p. 1577)

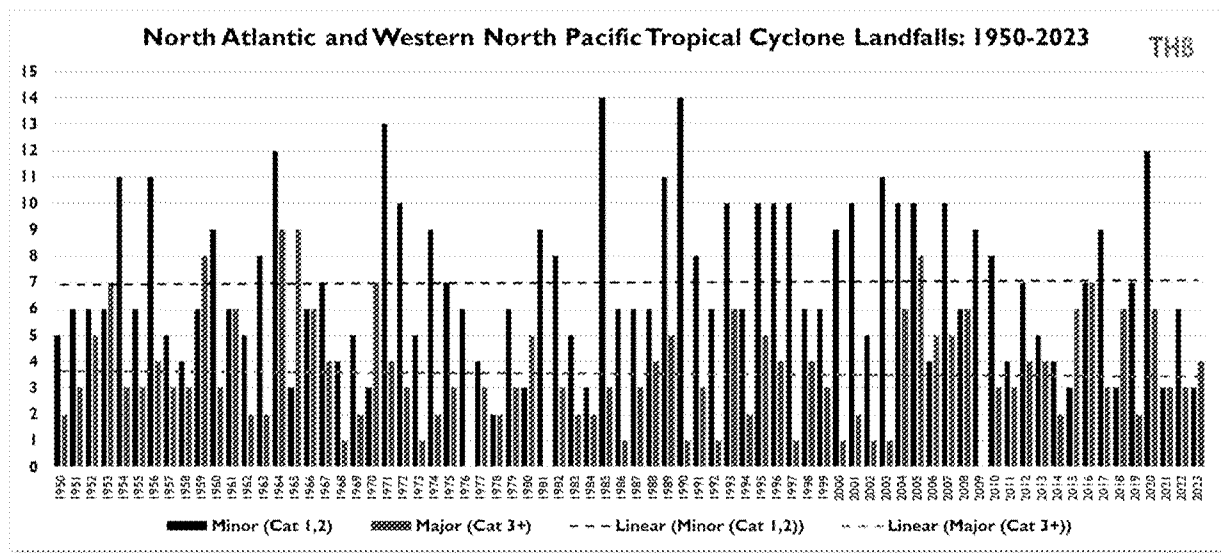
There are only two AR6 regions in which there is at least *medium confidence* that human-induced climate change has contributed to changes in meteorological droughts (Section 11.9). In South-western South America (SSW), there is *medium confidence* that human-induced climate change has contributed to an increase in meteorological droughts (Boisier et al., 2016; Garreaud et al., 2020), while in Northern Europe (NEU), there is *medium confidence* that it has contributed to a decrease in meteorological droughts (Gudmundsson and Seneviratne, 2016) (Section 11.9). **In other AR6 regions, there is inconclusive evidence in the attribution of long-term trends, but a human contribution to single meteorological events or subregional trends has been identified in some instances... In North America,**

the human influence on precipitation deficits is complex (Wehner et al., 2017), with low confidence in the attribution of long-term changes in meteorological drought in AR6 regions.

### 8.3. Extreme weather trends at global and continental scale

#### 8.3.1 Tropical Cyclones (TCs)

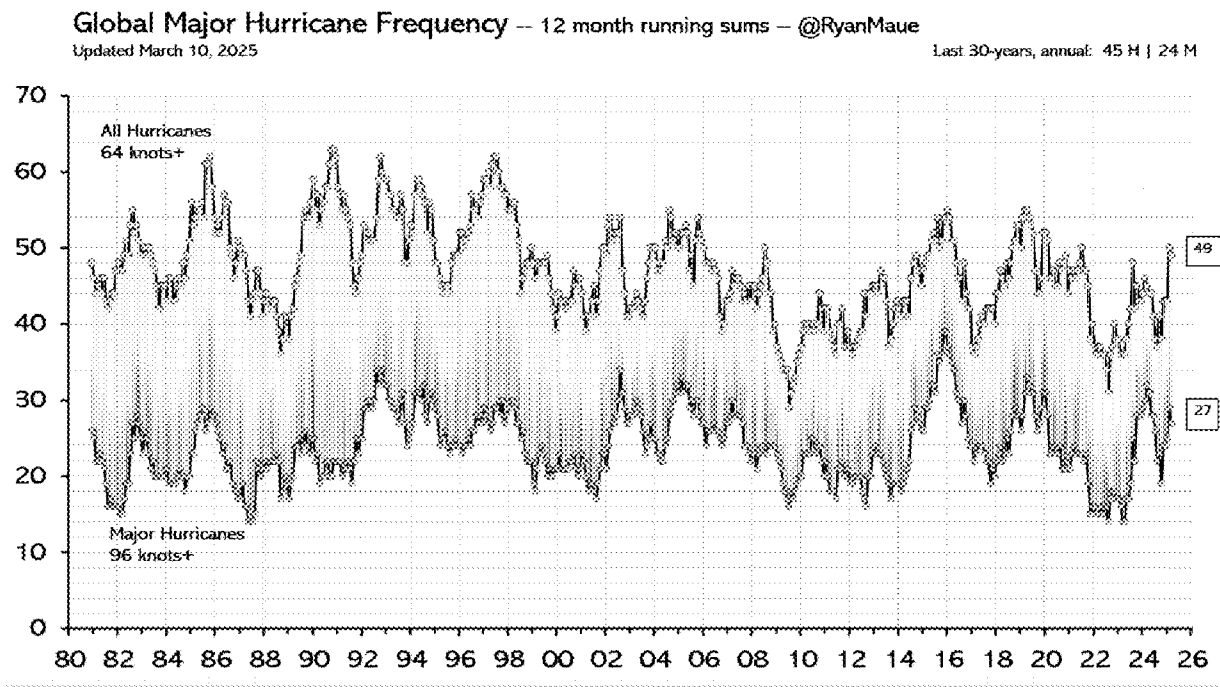
Hurricane strength records for the North Atlantic and the Western Pacific go back to 1950 and the record does not show an increase in either total or major TCs. Figure 8.3.1 was published by Roger Pielke Jr. as an update to the Best Track data series originally presented in Weinkle et al. (2012).



**Figure 8.3.1.** Tropical Cyclone Landfalls. Source: <https://rogerpielkejr.substack.com/p/global-tropical-cyclones>, Weinkle et al. (2012)

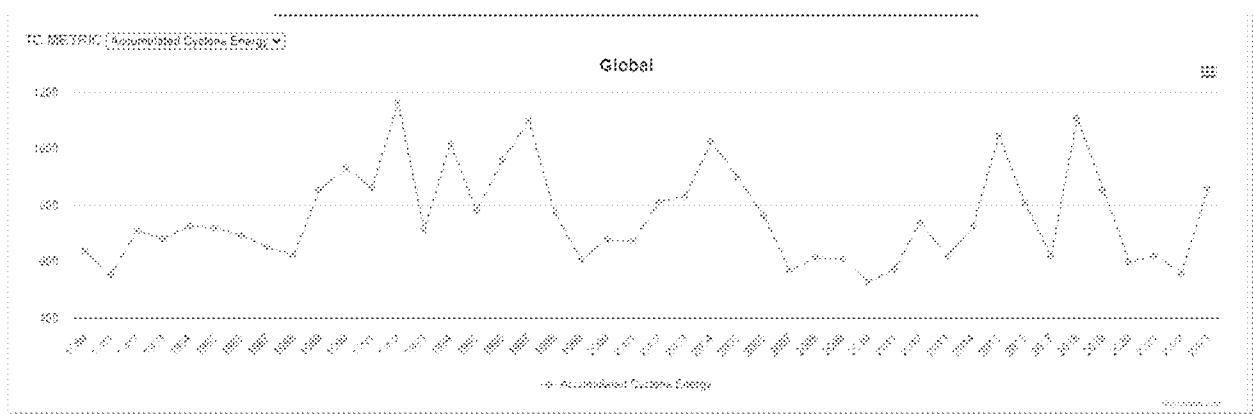
Similarly, Figure 8.3.2 (Maue 2025, <https://climatlas.com/tropical/>) shows that both all hurricanes and major hurricanes have not become more common since 1980, the period of rapidly growing human influences. In fact, both numbers have trended down slightly since the 1990s:





**Figure 8.3.2:** Global hurricane frequency. Source: Maue (2025)

A metric that combines the number, duration, and strength of TCs is the Accumulated Cyclone Energy (ACE) Index maintained at Colorado State University, shown in Figure 8.3.3. It clearly shows no long-term increase, in fact declining slightly since 1990.



**Figure 8.3.3:** Global Accumulated Cyclone Energy. Source: Klotzbach (2025)

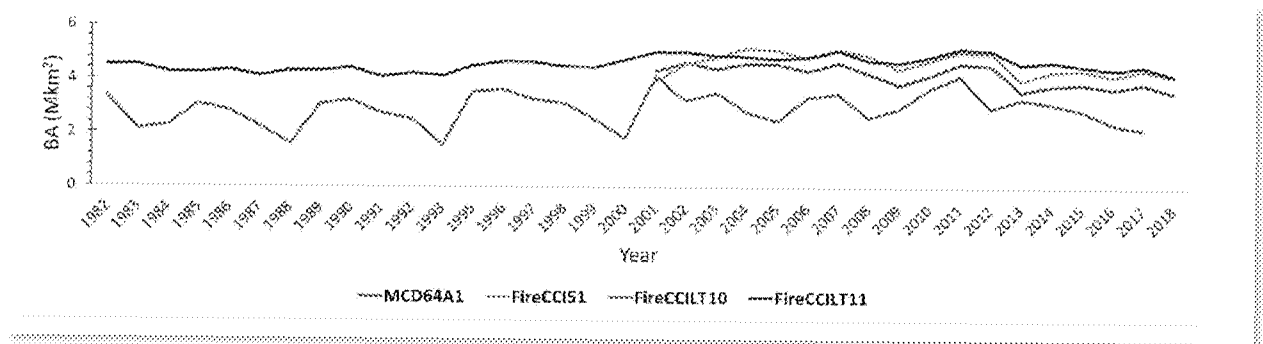
<https://tropical.atmos.colostate.edu/Realtime/index.php?arch&loc=global>

Note that Tu et al. (2024) report that the Power Dissipation Index (PDI), another different measure that combines hurricane number, duration, and strength, has either remained unchanged or has declined in all global oceanic basins since the mid-1990s.

Today's global climate simulations are too coarse to project changes in TCs directly. Rather, projections are derived from finer "downscaled" simulations or proxies involving sea surface temperatures, winds, and aerosols. By those methods, a warming climate is expected to show declining hurricane formation rates. (Chand et al. 2022). Climate models also project fewer Tropical Cyclones under future global warming, and even though models project they will increase in strength, the annual averages of rainfall maxima decline (Stansfield et al. 2020).

### 8.3.2 Wildfires

As shown in Figures 8.3.4 and 8.3.5 global wildfire activity as measured by European Space Agency peaked over a decade ago and shows a downward trend since.

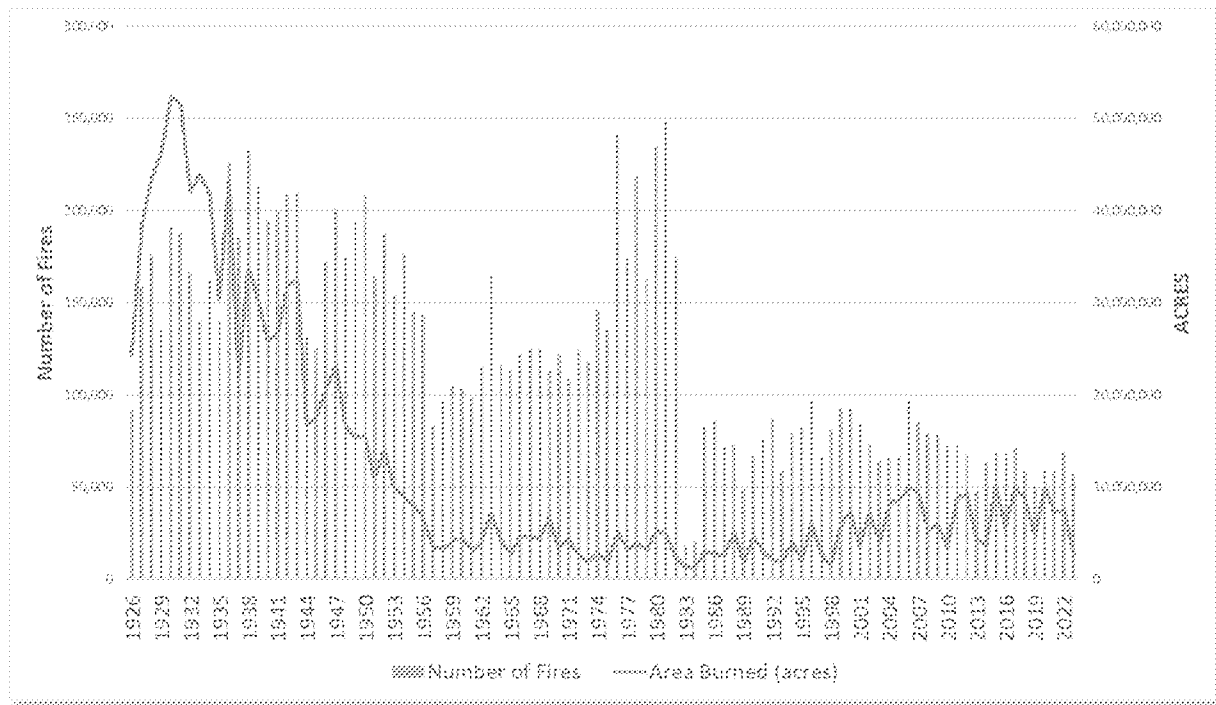


**Figure 8.3.4:** Global wildfire 1982-2018. Source: Copied from Oton et al. (2021). Note: the different coloured lines represent different data products based on satellites and algorithms used.



**Figure 8.3.5:** Global wildfire 2001-2018. Source: Copied from Lizundia-Loiola et al. (2021). Note: the different coloured lines represent different data products based on satellites and algorithms used

US data from the National Interagency Fire Centre (NIFC) from 1926 to 2023 are shown in Figure 8.3.6.



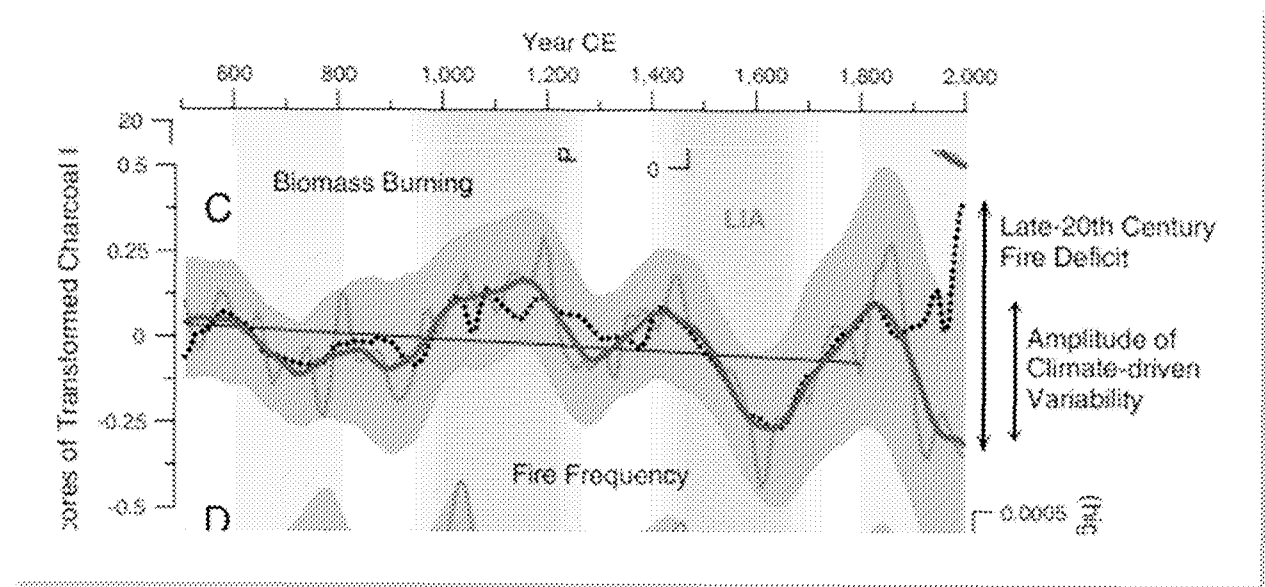
**Figure 8.3.6:** US wildfires 1926 to 2023. Source: National InterAgency Fire Centre data

Pre-2017 (archived)

[https://web.archive.org/web/20200212033452/https://www.nifc.gov/fireInfo/fireInfo\\_stats\\_totalFires.html](https://web.archive.org/web/20200212033452/https://www.nifc.gov/fireInfo/fireInfo_stats_totalFires.html). 2018-2023: <https://www.nifc.gov/fire-information/statistics/wildfires>

Note the NIFC has removed the pre-1960 data from its current website. They claim it is because measurement methods changed after 1960. This explanation seems inadequate since agencies blend temperature and extreme weather data series in other contexts when measurement systems changed. In this case if anything the measurement of wildfires has improved since the early 20<sup>th</sup> century so any bias will be towards understating early wildfire counts. Nonetheless just focusing on the post-1985 interval the number of fires is not increasing. The area burned did increase but only until about 2007.

It is difficult to establish a natural baseline for wildfire activity because of active fire suppression activity since 1900. Paleoclimatic evidence indicates, however, that past wildfire activity was much higher than at present. Marlon et al. (2012) used sedimentary charcoal layers to reconstruct fire history of western US for the past 1400 years. They also fit a model to predict expected fire activity as a function of climatic conditions. The results are summarized in Figure 8.3.7 below (from Figure 2 in their paper).

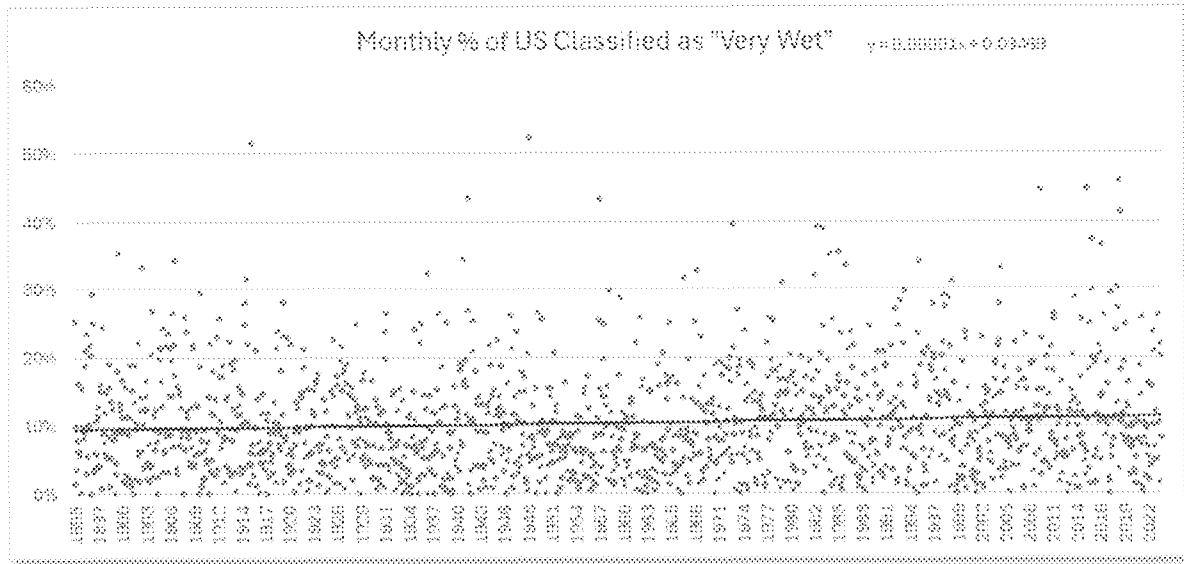


**Figure 8.3.7:** Fire frequency and fire deficit in the US. Source: Copied from Marlon et al. (2012)

In their figure the red line shows the smoothed charcoal record and the black dotted line shows the predicted charcoal record based on the statistical model. The gap at the end implies there has been a growing wildfire deficit over the 20<sup>th</sup> century. In other words, however much fire was observed in the 20<sup>th</sup> century it was less than what would have been observed in previous centuries based on the climatic conditions. Parks et al. (2025) likewise find that despite the recent increase in wildfire burn area in North America, a significant wildfire deficit remains relative to historical wildfire regimes.

### 8.3.3 Precipitation

Figure 8.3.8 shows that US long term data from NOAA shows an insignificantly increasing tendency toward extreme wetness (+0.001% per year)



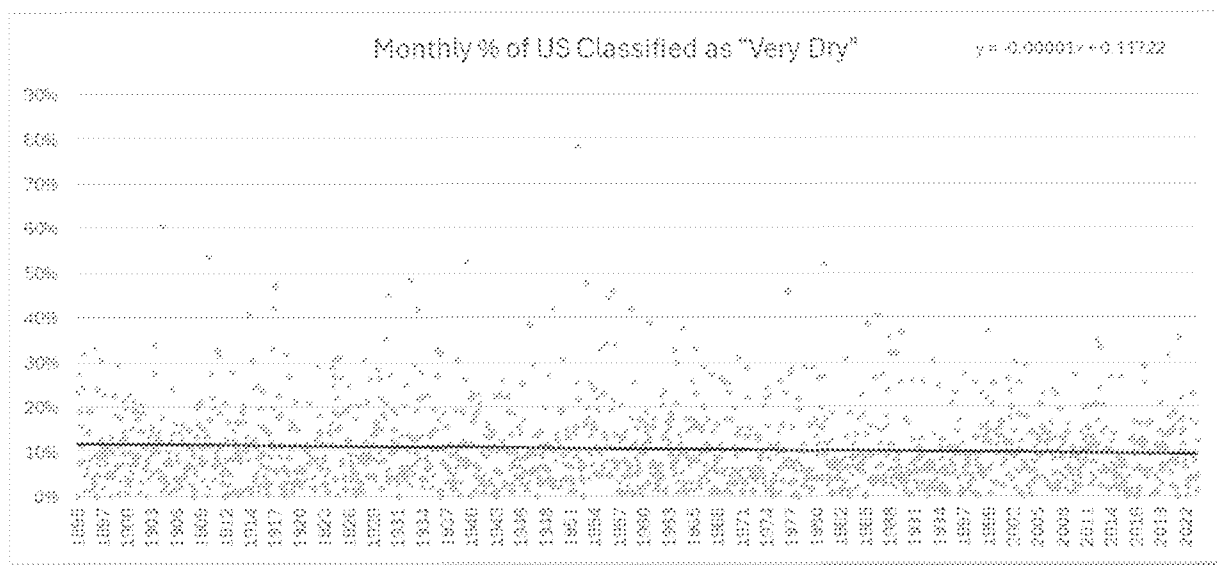
**Figure 8.3.8:** Long term US wetness (%). Source: NOAA

<https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0>

Precipitation will be discussed further in the review of CONUS data below.

### 8.3.4 Drought

As shown in Figure 8.3.9 US long term data (NOAA) shows an insignificantly declining tendency toward extreme dryness (-0.001% per year)



**Figure 8.3.9:** US dryness (%) 1895—2023. Source: NOAA  
<https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0>

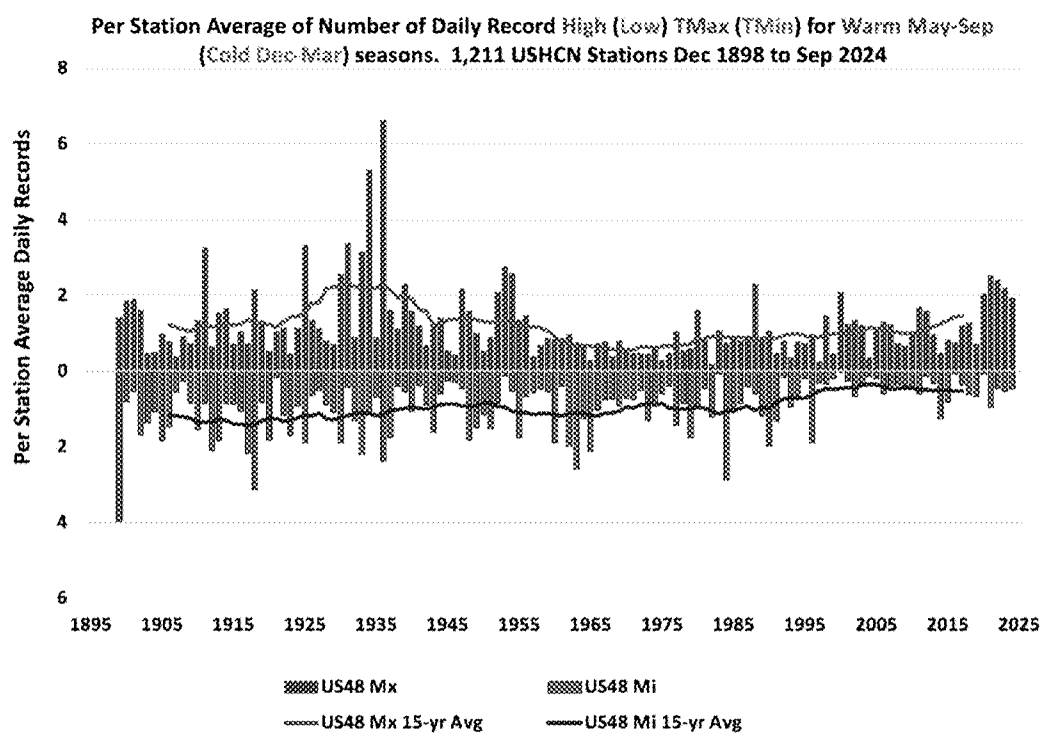
Kogan et al. (2020) examines a 38-year high-resolution satellite-based drought measure and concludes that global drought has not intensified and is not connected to climate change: “it is possible to state firmly that global and main grain countries’ drought area and intensity trends have not been following global climate warming since 1980’s.”

## 8.4. Temperature and precipitation extremes in the Contiguous US (CONUS)

### 8.4.1 CONUS daily temperatures are becoming less extreme

Daily maximum temperatures in the warm season (TMax, May-Sep) and daily minimum temperatures in the cold season (TMin, Dec-Mar) are available beginning in Dec 1898 (126 years). The dataset consists of 1,211 CONUS stations designated as United States Historical Climate Network or USHCN stations (Quinlan et al. 1987, Karl et al. 1990). These stations were selected by NOAA as having the fewest problematic issues with gaps, station moves and instrument changes. Where gaps still exist, nearby stations (bias-corrected) were merged so that the median volume of data available for a station is 98%. Although there are certainly errors in the dataset, with over 1,000 stations we can have relatively high confidence in any underlying signal that might be discovered.

We begin with the question of whether the occurrence of daily record high or low temperatures changed has changed since Dec 1898. Each warm-season has 153 days (1 May to 30 Sep) and each cold-season has 122 days (1 Dec to 31 Mar). For each station and day, we calculated the year in which the record highest (lowest) temperature occurred. With 126 years of observations, if there were no temperature trends over time, the expected number of records for TMax would be 1.21 ( $=153/126$ ) per station per year and for TMin 0.96 ( $=122/126$ ) per station per year. Figure 8.4.1 indicates the observed distribution in time of the occurrence of these extreme events.

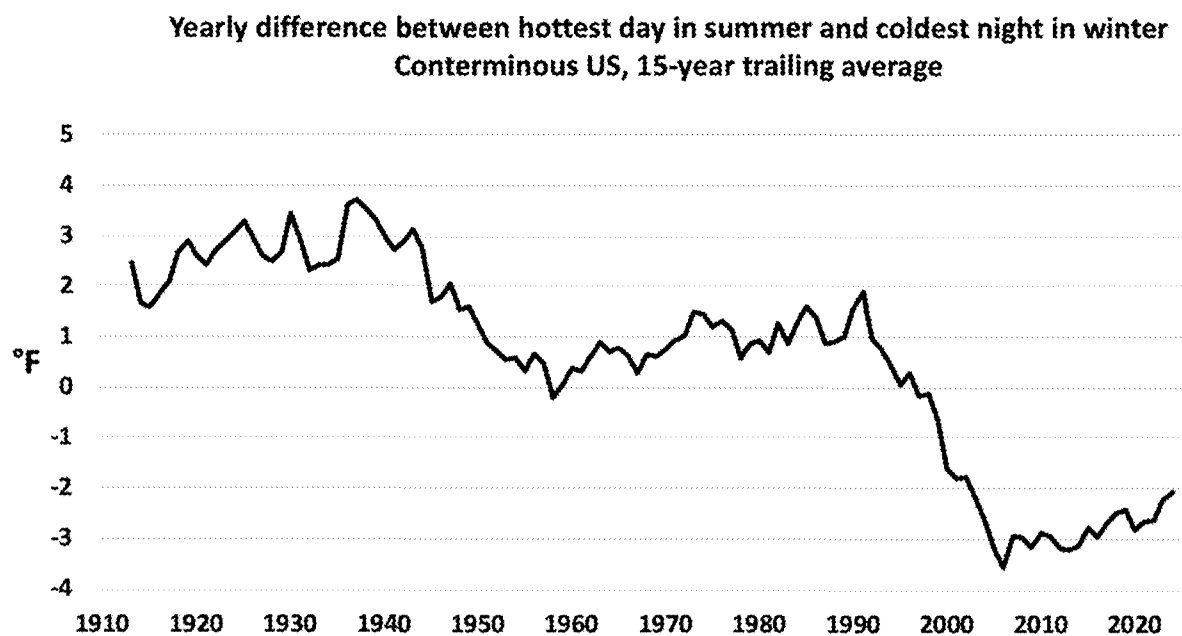


**Figure 8.4.1** Number of daily record High (red) and Low (blue) for warm and cold seasons in the CONUS. The lines represent the 15-year running, centered average. Source: 1,211 USHCN stations supplemented as needed to achieve a minimum of 92% of observations in the 126-year period since Dec 1898.

The results indicate a common feature in many metrics of warm-season extremes in the CONUS - the exceptional heat of the 1920s and especially the 1930s, peaking in 1936. On a per-station average, 60% of the TMax records and 59% of the TMin records occurred in the first half of the period (1899-1961).

On the cold side, the Valentine's Day Arctic outbreak in Feb 1899 stands as the most extensive cold extreme experienced by the CONUS, with 1917 2<sup>nd</sup>. The frequency of cold records has declined, especially over the last quarter of the period in which only 13% of the extreme cold events were measured. In contrast, 25% of the extreme TMax records were achieved in the last quarter in accordance with statistical expectations. These general features have been noted in past assessments (IPCC AR5, IPCC AR6, NCA4, NCA5). Combining the two records the overall reduction in numbers of both cold and hot extremes over the past century indicates a climate less prone to extremes.

This pattern is also shown in Figure 8.4.2. For each station and for each year the hottest warm season and coldest cold-season temperatures were calculated and converted to anomalies relative to the station's long term warm and cold season (respectively) averages. Then the differences between these were computed by station and geographically-averaged over all stations, thus yielding an annual measure of the expected range of local extreme temperatures for each year. Figure 8.11 shows the 15-year trailing average of this measure which has clearly declined over the past century.



**Figure 8.4.2.** 15-year trailing average of the difference each year of each station's hottest warm-season TMax and coldest cold-season TMin relative to the long-term average.

The average difference for each station between the hottest summer TMax and coldest winter TMin has declined about 5°F in the past 126 years. The decline is due mostly to warming winter TMin, but a decline in the magnitude of summer TMax is also a factor. The rise in TMin has been strongly related to the growing presence of manufactured surfaces around the weather stations over the last 100+ years (Spencer et al. 2025).

Summarizing Figures 8.4.1 and 8.4.2, while temperature extremes are regularly experienced in the US and attract a great deal of media attention, long term records show the US climate has become less extreme over time (milder) when measured in terms of the range between warm season maxima and cold season minima.

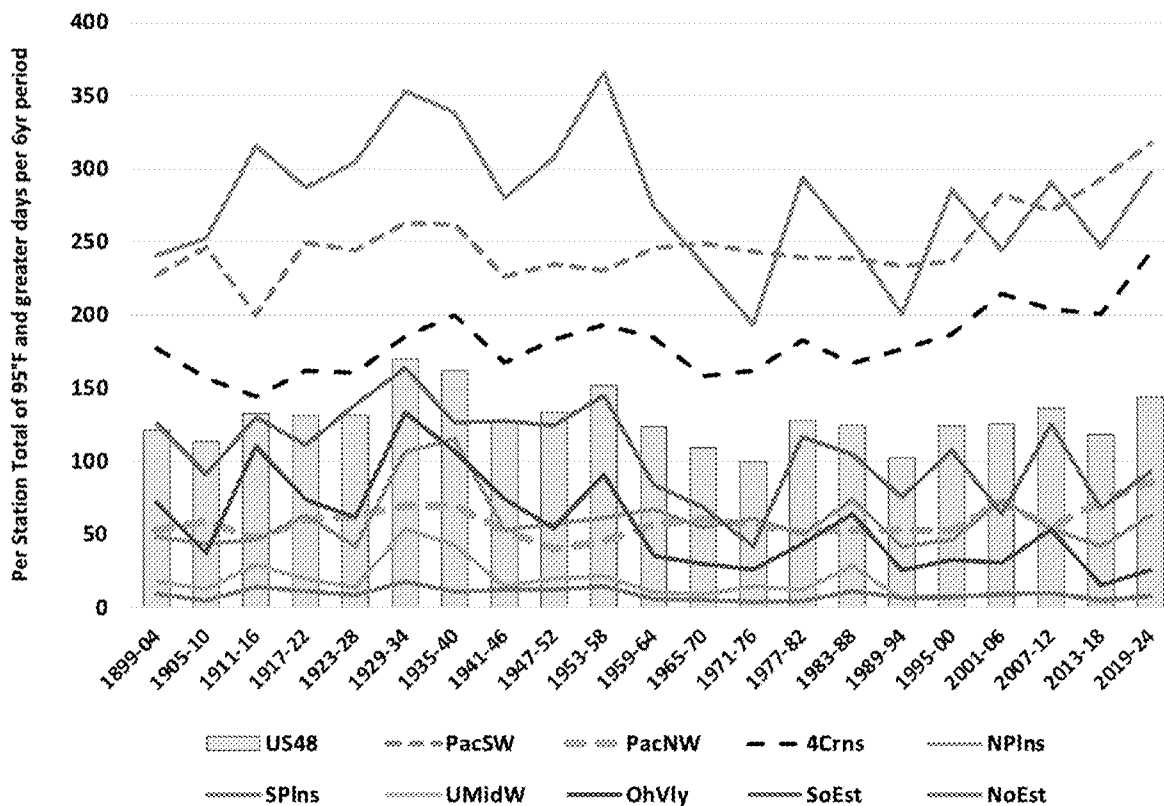
#### 8.4.2 Exceedances of a heat threshold



Under the heading of “The Risk of Temperature Extremes is Changing”, the most recent US National Climate Assessment report (NCA5) notes the increase in a threshold metric of number of days at or above 95°F, stating,

“The western US has been particularly affected by extreme heat since the 1980s ..., experiencing a larger increase in days over 95°F, as would be expected given the greater warming in that region relative to the eastern US. Several major heatwaves have affected the US since 2018, including a record-shattering event in the Pacific Northwest in 2021.”

Are the occurrences of 95°F days changing? In a climate as varied as that of CONUS, threshold statistics can be misleading. A region with many stations that have near 95°F TMax average temperatures in the summer might see large swings in the metric when only small changes in average temperature occur. Elsewhere with stations that either rarely or virtually always achieve 95°F TMax temperatures, a small change will not impact the results much at all. In the past 126 years, the average CONUS station experienced 129 days exceeding 95°F per 6-yr period, but the regional values range from 278 in the Southern Plains to 9 in the Northeast. Thus, one needs to view such threshold analyses with caution.



**Figure 8.4.3.** Total number of days  $\geq 95^{\circ}\text{F}$  in 6-yr periods, US 48 (bars) and regions (lines).

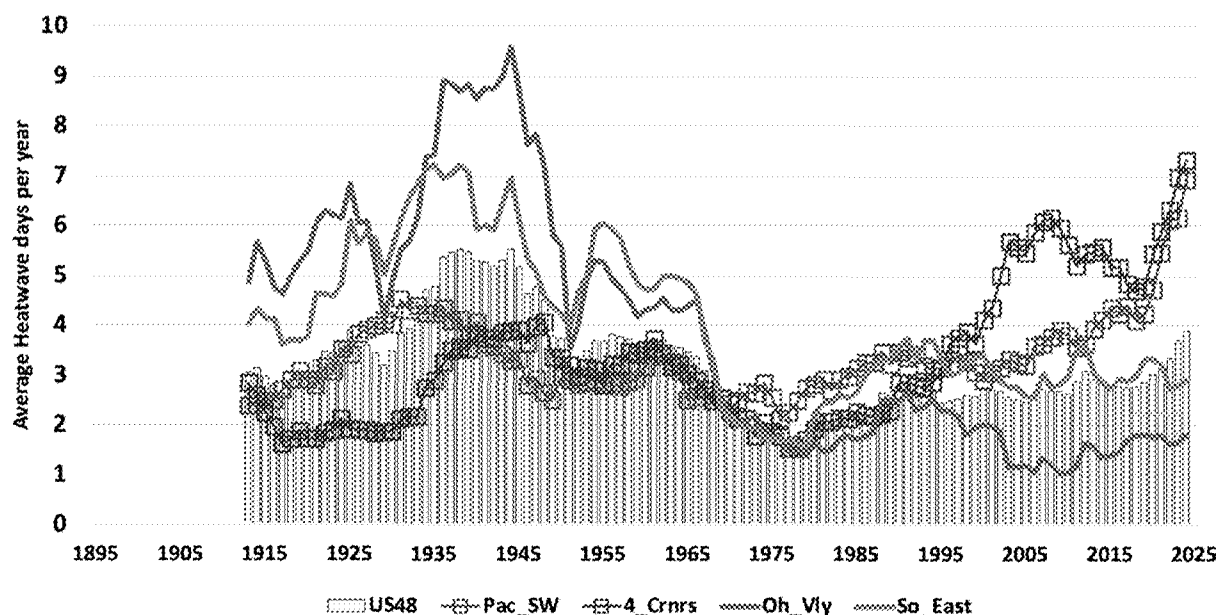
In Fig. 8.4.3 we see that only three of the nine regions, all in the West, have experienced upward trends in the number of 95°F or hotter days (dashed lines). The CONUS as a whole has not and the other six regions have experienced declines.

The Pacific NW heatwave of 2021 is referenced as of the NCA5 claim, an event we examine more closely in Section 6.4. The evidence indicates it was a “black swan” event; *i.e.*, a single, unprecedented event in the record, not part of a pattern of increasing extreme heat. For example, the 5-day average tropospheric grid-point temperature anomaly over the Pacific NW during that event was +10.8 C, the most extreme NH grid point summer anomaly in the 46 years from over 4 million grids. In contrast, the global anomaly during that time was virtually zero (+0.03 C, Mass et al. 2024).

The heading “The Risk of Temperature Extremes is Changing” suggests positive trends are now being observed in threshold temperatures on a widespread basis, but that is not evidenced in the combined CONUS results of the figures above.

### 8.4.3 Heatwaves

Heatwaves (consecutive days that exceed an extreme threshold) have a greater societal impact than a single daily record. We measure “Heatwave Days” here as the count of all days in May-Sep each year that exceed the 90<sup>th</sup> percentile and that lie within a run of at least six consecutive days. This is equivalent to the method used in NCA5 except that the reference period here is the entire record 1899-2024 while NCA5 truncated the reference period to 1961-1990, a cool time. That truncation boosts positive results (days exceeding the 90<sup>th</sup> percentile) in periods warmer than the reference period, especially starting in 1960 and moving to the present (see *Urban Influences* below).



**Figure 8.4.4** 15-year trailing average of number of heatwave days per year per station in the CONUS (bars) and four regions: Pac\_SW (purple squares, CA, NV), 4\_Crnrs (red squares, AZ,NM,UT,CO), Oh\_Vly (blue, MO, IL, KY, TN, IN, OH, WV) and So\_East (green, MS, AL, GA, FL, SC, NC, VA).

Figure 8.4.4 indicates again the excessive heat of the first half of the 20<sup>th</sup> century, primarily in the eastern two-thirds of the nation, as seen in the regional values for the Ohio Valley and the Southeast as examples. The West has seen a recent increase of heatwave days and the two regions with the highest number are shown, the Pacific Southwest and the Four-Corners (NCA5). This indicates that

the background warm season circulation favored heatwaves in the eastern portions of the country in the first half of the 20<sup>th</sup> century, but in the 21<sup>st</sup> century the patterns have favored heatwaves in the West. For CONUS as a whole, heatwaves are no more common today than they were a century ago.

Of interest here is the regional variation of this metric. The four northern regions (Pacific NW, Northern Plains, Upper Midwest, and Northeast) on average experience 15 to 27 heatwave days per 15-year period. In contrast, the five southern regions (Pacific Southwest, 4-Corners, Southern Plains, Ohio Valley and Southeast) see 37 to 54 such days, essentially twice as many. This suggests the summer circulation pattern is more prone to stationary events in the southern regions while transient systems in the northern regions are more common and thus cut short these potentially longer events.

#### Urban influences

The NCA5 directs readers to the website <https://www.globalchange.gov/indicators/heat-waves> (USGCRP 2023) to view the number of urban heatwaves by decade from the 1960s. The figure shows a monotonic increase in each decade from 2 occurrences per year in the 1960s to 6 in the 2020s. The definition of a heatwave is an unusual but practical measure of human discomfort - a period of at least 2 consecutive days when the minimum apparent temperature (combination of temperature and humidity) exceeds the 85<sup>th</sup> percentile. Note too, the dataset is limited to the 50 largest U.S. cities.

These increasing values since 1960 presented in USGCRP (2023) are entirely reasonable, but are unrelated to GHG emissions for at least two reasons. Urbanization in these cities is a major factor in the rise of TMin relative to co-located TMax and relative to TMin at rural stations. Also, the 1960s was the coldest decade and 1970s the second coldest decade since the 1910's, so this starting date preconditions the time series to show increases. This does not dismiss the real rise in nighttime temperatures in major U. S. cities and the societal impacts associated with these changes. However, we note for a variety of reasons, that summer TMax (especially in rural areas) serves as better response variable for detecting potential changes in heatwaves influenced by changes in the background climate due, for example, to increasing GHGs (Christy et al. 2009). For the CONUS as a whole, the evidence in this section suggests GHG emissions have had little-to-no effect on heatwaves.

#### 8.4.4 Extremes in daily precipitation.

Because precipitation involves a discrete phase change (water vapor to liquid), it is stochastic and episodic in character and requires careful statistical treatment to understand variability over long time periods (see *8.1 Introduction*). The US National Climate Assessments (NCA4, NCA5) have highlighted an increase in the occurrence of the heaviest precipitation events (defined in different ways) primarily in the eastern half of the CONUS, especially the Northeast, when starting in either 1901 or 1958. Interestingly, the regional variations indicate that the largest increases in extreme events are in the Northeast and the smallest in the West, a trend counter to the changes in temperature extremes.

McKittrick and Christy (2019) examined long-term and consistent station observations of daily precipitation to test some of these NCA claims for the Southeast and West Coast. When the time series were extended back in time (as far as 1872 in some cases) or when starting later (1978), there were no significant trends for either region. For this report we updated these findings with similarly constructed observations from 29 stations on the Pacific Coast (1893ff from San Diego CA to Blaine WA), 24 stations in the humid Southeast (1872ff from Austin TX to Washington DC), and 21 stations in the Northeast (1888ff from Buffalo NY to Gardiner ME). The results were as follows.

#### Pacific region:

- Average precipitation trend is significant (downwards) in Astoria, insignificant elsewhere.
- The trend in rainfall variance is positive and significant in Big Sur, insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Aberdeen and Big Sur and negative and significant in Newport (insignificant elsewhere).
- Averaged over all stations in the region none of these three trend parameters is statistically significant.

#### Southeast region:

- The trend in average precipitation is positive and significant in Mobile and Quitman, insignificant elsewhere.
- The trend in rainfall variance is positive and significant in Mobile, insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Vicksburg and Norfolk, insignificant elsewhere.
- Averaged over all stations in the region none of these three trend parameters is statistically significant

#### Northeast region:

- The trend in average precipitation is positive and significant in 9 of 21 locations and in the region averaged overall.
- The trend in rainfall variance is positive and significant in Portland, Albany and Buffalo, insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Portland and Gardiner, insignificant elsewhere.
- Averaged over all stations in the region the trend parameters for variance and maximum precipitation are not statistically significant.

#### Pacific Coast heavy rainfall events

The Pacific Coast receives considerable precipitation from Atmospheric River (AR) events which often last more than a day or two (e.g., Gershunov et al. 2017, Pan et al. 2024). The worst-known such event in recent history was the ArkStorm that occurred between December 1861 and January 1862, which dumped nearly 10 feet of rain in parts of California and submerged the entire Central Valley for weeks under as much as 15 feet of water (Brewer 1930, Null and Hulbert 2007). Paleoclimate research has found six megastorms more severe than 1861–1862 in California during the last 1800 years, occurring at intervals of 300 years or so (Porter et al. 2011).

#### SIDEBAR: Perils of short data records

San Francisco provides a good case study of the limitation of using short historical samples to characterize natural variability of extreme events. Suppose we use a 130-year sample of daily San Francisco precipitation from 1895 to 2024 and we look for 3-day, 5-day, 14-day and 30-day rainfall records. The results are as shown in Table 8.2.

| Event  | Record<br>(inches) | Year |
|--------|--------------------|------|
| 3-day  | 6.94               | 2023 |
| 5-day  | 8.55               | 2023 |
| 14-day | 12.62              | 2023 |

|  |        |       |      |
|--|--------|-------|------|
|  | 30-day | 18.93 | 1998 |
|--|--------|-------|------|

Table 8.2: Extreme rainfall records, San Francisco, 1895-2024.

The records all cluster in the more recent data. 2023 appears to be an exceptional year and since it is near the end of the sample it might suggest that the climate has shifted into a more hazardous state, perhaps as a result of human influences.

But the picture is very different if we use a sample that begins 45 years earlier, in 1850. Table 8.3 shows that the record-setting events then all happened in the 1860s. Furthermore 2023 is now not even in 2<sup>nd</sup> place but falls to 3<sup>rd</sup> or 4<sup>th</sup>. Also, comparing the records of the two charts the extreme precipitation events in 1862 and 1867 involved considerably more rainfall than the 1998 and 2023 events, with 14- and 30-day totals about 50 percent higher.

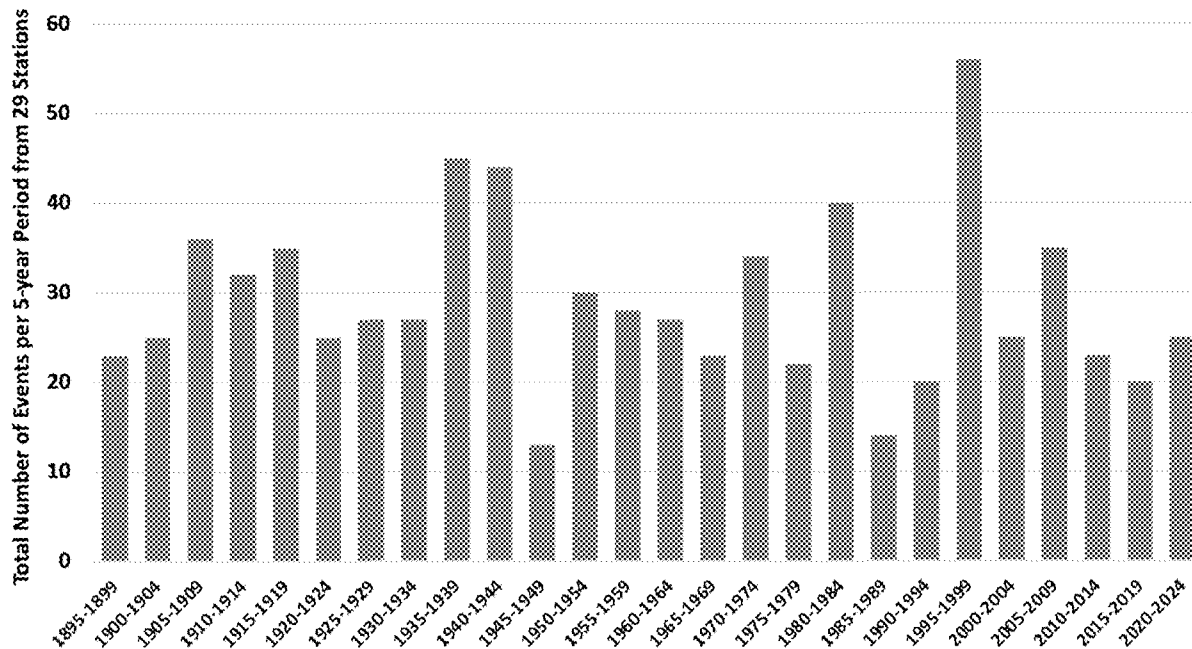
| Event  | Record<br>(inches) | Year | Rank<br>130-yr<br>extreme | of |
|--------|--------------------|------|---------------------------|----|
| 3-day  | 8.85               | 1867 | 3                         |    |
| 5-day  | 9.80               | 1867 | 3                         |    |
| 14-day | 19.05              | 1862 | 4                         |    |
| 30-day | 28.25              | 1862 | 2                         |    |

Table 8.3: Extreme rainfall records, San Francisco, 1850-2024.

The range of natural variability is made even more remarkable when paleoclimate evidence is examined. Porter et al. (2011) discovered that in the past 1,800 years at least six megastorms were more intense than the devastating 1861-62 ArkStorm that struck the region. Evidently such extreme events have impacted the region about every 300 years, though not since 1895.

This example illustrates the limitations of using relatively short climate periods (~130 years) to assess the character and range of natural variability in general and of extreme events in particular. Accurate representation of the full range of natural variability is necessary for any attribution analyses (see 6.4). Infrastructure planners, emergency management institutions and attribution scientists would understand the significant mischaracterization of the magnitude of a future extreme if based only on the last 130 years. In this case, a single time-sample of 130 years provides an underestimation of the extreme value by up to 50% determined when adding only 45 more years of observations. Compared to millennial-scale paleoclimate evidence, an even greater underestimation would occur. An important lesson is that the climate can deliver great surprises on its own, even without human influences.

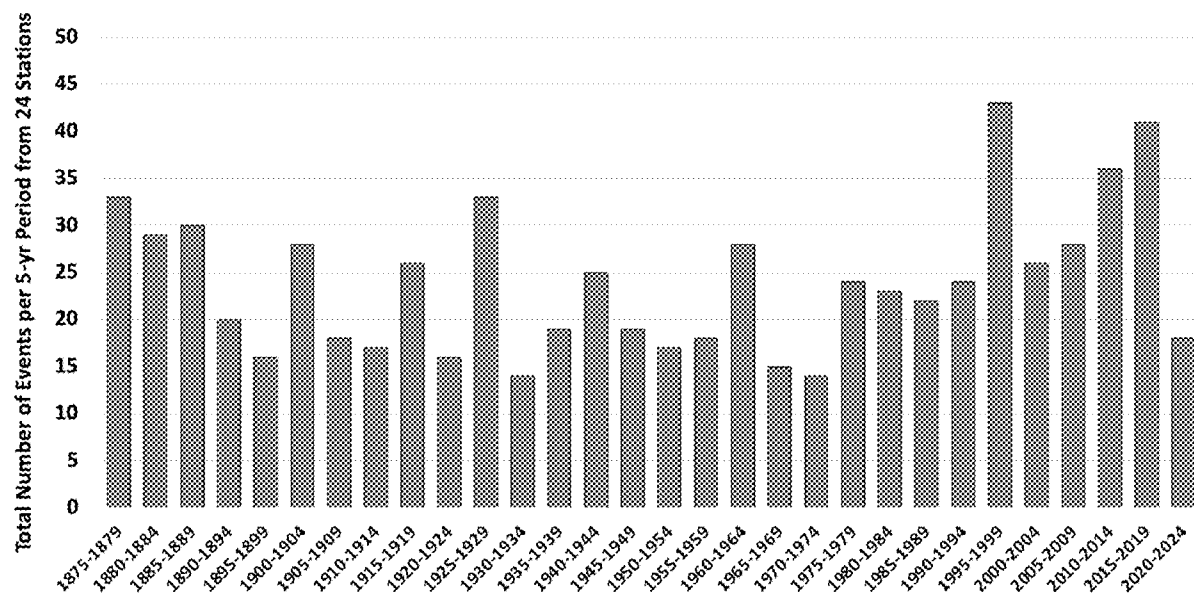
We examine occurrences of 5-day deluges as follows. In a 130-year span there are 26 5-year intervals. At each location we computed the 5-day precipitation totals throughout the year and selected the 26 highest values. A single year may have more than one of the 26 heaviest. Each of those can be thought of as 1-in-5yr events. If there are no trends in precipitation then the total number of these events across all stations should be evenly spread out over the years. In Fig. 8.4.5 we show the distribution in time of these events. The deluges associated with the massive 1997-98 El Niño event are readily apparent. While erratic, as is typical of these types of precipitation metrics, there is no indication of a tendency to become more frequent over time.



**Figure 8.4.5.** The time distribution by 5-year periods of the 26 heaviest occurrences for each station (i.e., nominal 1-in-5 year event).

#### Southeast heavy rainfall events

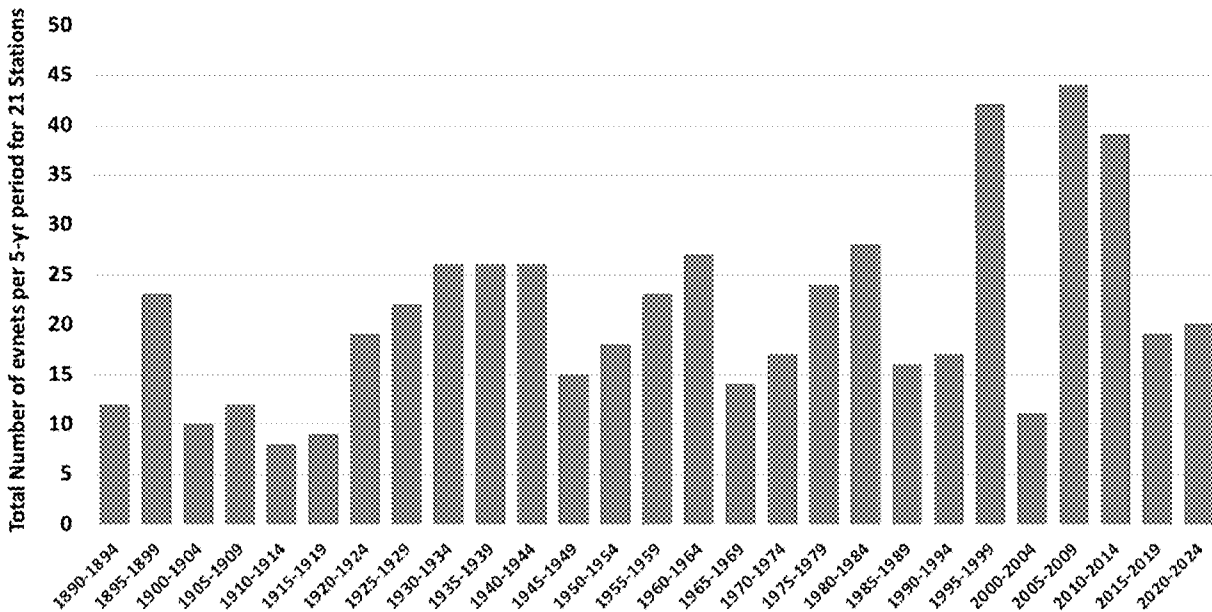
The temporal pattern of 5-day totals of the 1-in-5yr heavy events in the humid Southeast (Figure 8.4.6) is generally unremarkable, though a cluster of higher values appears in 1995 to 2019. The increase in those years is due largely to the 4 northeastern-most stations of Wilmington NC, Weldon NC, Washington DC, and Norfolk VA. This confirms the pattern indicated in NCA4 and NCA5 of a tendency for an increasing frequency of heavy events, due to a temporal clustering of tropical storms from eastern NC to Maine discussed below. Otherwise, the remaining 20 stations show an unremarkable temporal distribution of heavy events.



**Figure 8.4.6.** As above but for the 30 heaviest 1-in-5yr events for 24 stations in the humid Southeast from Austin TX to Washington DC in 5-year bins for 1875-2024.

#### Northwest heavy rainfall events

Fig. 8.4.7 shows the 27 (1-in-5yr) heaviest 3-day events for the last 135 years in 21 stations in the Northeast (including Montreal Canada). We use 3-day totals here as this produced the largest variations in time. In this region, 72% of the events occur during June to October and are dominated by tropical incursions of hurricanes, tropical storms or tropical storms that transition to extratropical systems. According to NCA4 and NCA5 this region experienced the largest increases in extreme events, so it shall be examined more closely.



**Figure 8.4.7.** Time distribution of the heaviest 27 (1-in-5yr) heaviest 3-day precipitation events for 21 stations from NY to ME, including Montreal.

Howarth et al. (2019) report differences in the Northeast between two 18-year periods: 1979-96 and 1997-2014 (a similar region as in Fig. 8.16 that includes PA and NJ) of various precipitation extremes. One metric which indicated a dramatic increase (317%) was found for 24-hr events > 6 inches. This high increase is due to the very small numbers of such events of which there were only 6 in the first period and 25 in the second as reported for 58 stations. This high percentage increase is due to the very small numbers of the events; only 6 in the first period and 25 in the second. Most of the stations, did not record such an event suggesting these erratic, episodic events over brief, 18-yr periods, need scrutiny by additional statistical methods.

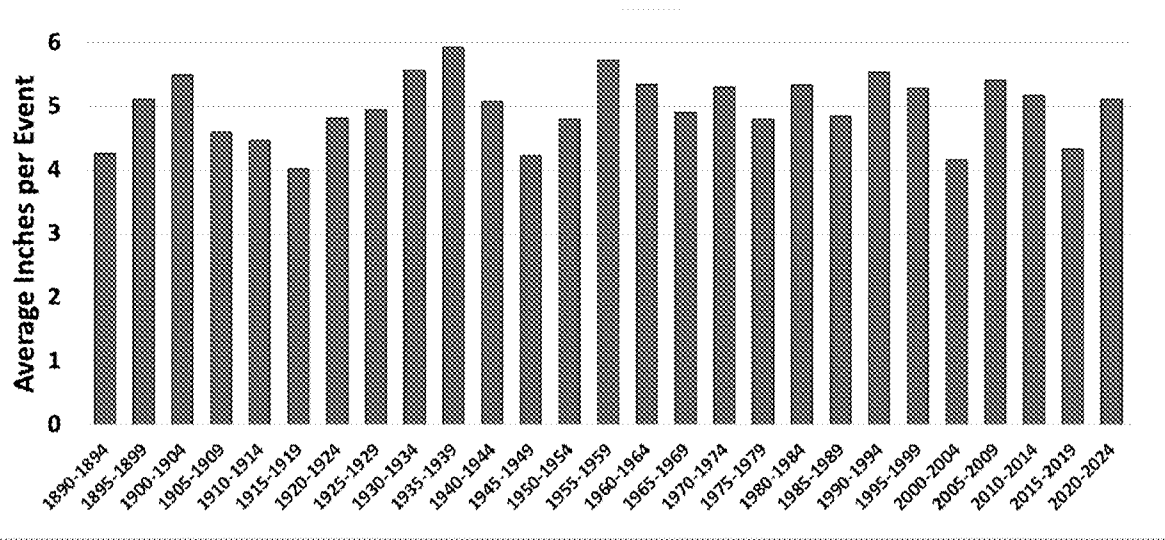
Using the information in Fig. 8.4.7 over the same years as Howarth et al. we find a 51% increase in the frequency of heavy events between the two periods. One can see in Fig. 8.16 that it was unfortunate that Howarth et al. ended in 2014 prior to a return to the long-term average of such events.

A feature of Howarth et al. is the use of single day totals which is questionable because extreme events are often spread across the time-of-observation boundary. Thus stations measuring at 0700 LT versus those at Midnight will have differing results for a particular event which would then have major impacts on counting these events. We use the 3-day totals in Fig. 8.4.7 to be sure to capture the extent of these extreme downpours. In any case, we can confirm that the period 1997 to 2014 experienced a cluster of heavier events as Howarth et al. have documented.

Howarth's most remarkable claim (317% increase in 6" days) is potentially misleading because it is a threshold statistic (see Section 8.4.2 above) and a ratio of small numbers over a short period. The result is not representative of *relative* extreme events for the whole region since the majority of stations never experienced a 6" total. Fig. 8.16 above determines the same number of events for each station (27 heaviest events) whose heaviest values ranged from 4.4" to 12.5" and their 27<sup>th</sup> heaviest values ranged from 3.3" to 5.0". This analysis thus allows each station to be equally represented. In



other words, if there is a region-wide increase in heavy events, it should be seen in the sum of all stations. Note too that the period of record here is 135 years vs. 36 years of Howarth et al. Except for three 5-year periods between 1995 and 2014 there is nothing statistically remarkable about the results in Fig. 8.4.7.



**Figure 8.4.8.** Average amount of precipitation falling in the 1-in-5yr events for the NE stations.

An interesting aspect of Northeast precipitation is that there has been no change in the amount of precipitation per heaviest event, as shown in Fig. 8.4.8. The trend is only  $+0.02''/\text{decade}$ . The highest amount, 1935-39, includes the Great New England Hurricane of 1938, one of the rare major (Category 3 or higher) hurricanes to strike the region. The results in Figs. 8.4.6 and 8.4.7 suggest that though there was an uptick in the number of events during the period 1995 to 2014; the events, individually, are not becoming more intense.

Jong et al. (2024) document the increase of tropical influences on precipitation events in the Northeast since 1959 and concluded, "The autumn extreme precipitation trend over the Northeast US is primarily attributed to tropical cyclone-related events since the 1990s." The question then becomes, was the temporal clustering of tropical systems in 1997-2014 which affected the Northeast a response to increasing GHGs? Jong et al. examined CMIP-6 model output which suggests that there will be fewer such systems in the 21<sup>st</sup> century but that the intensity of the rainfall events might increase. This conjecture is not seen in Fig. 8.17 where the amount-per-event has remained steady over the 135-year period.

For substantial urban areas there is some evidence to indicate the heaviest rainfall events may be redistributed due to the impact urban infrastructure has on the local weather (e.g., Pielke Sr. et al. 2011, Zhang et al. 2018, Yang et al. 2024). Yang et al. state, "Cities that experience compact development tend to witness larger increases in extreme rainfall frequency over downtown than their rural surroundings, while the anomalies in extreme rainfall frequency diminish for cities with

dispersed development.” While this is an important insight to consider, the effect on the specific stations used in this analysis is unknown, or at least not detectable in Fig. 8.17.

In summary, the evidence from the historical record of extreme precipitation events in the CONUS is generally not consistent from region to region so that inferences regarding trends and their projections are wrought with significant uncertainty. In most regions and perhaps all, it is our opinion that the very nature of the erratic and episodic character of extreme precipitation events renders the discovery of statistically significant changes, including a relationship to CO<sub>2</sub> concentrations, a result yet to be achieved (McKittrick and Christy 2019).

## 8.5 Summary

Based on the content provided in the document, here are the five most important takeaways:

1. Limited Detection of Anthropogenic Signals: The IPCC has asserted high confidence in detecting an anthropogenic signal in only 4 out of 34 weather impact categories, and medium confidence in 4 more. For the remaining 26 categories, no anthropogenic signal is claimed to be detected.
2. Slow Emergence of Trends: Even under the most extreme forcing scenario (RCP8.5), the IPCC expects very few anthropogenic trends to emerge within this century for most weather impacts.
3. Natural Variability Dominance: Natural variability continues to dominate patterns of extreme weather systems. Simple assertions of trend detection are often complicated by regional heterogeneity and trend reversals over time.
4. RCP8.5 Scenario Implausibility: The document notes that the RCP8.5 scenario is described as an implausible high-end storyline, not a "base case" or "business-as-usual" projection.
5. Conflicting Messages on Attribution: The document mentions that AR6 (IPCC Sixth Assessment Report) offers conflicting messages about the attribution of extreme weather to anthropogenic causes, highlighting the complexity and uncertainty in this area of climate science.

These takeaways emphasize the nuanced and complex nature of attributing extreme weather events to climate change, and the importance of considering natural variability and uncertainty in climate projections.

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## 9. Changes in Sea level

Arguably the most important climate impact driver that is unambiguously associated with increasing temperatures is global sea level rise. Global warming increases sea level rise through thermal expansion of the volume of sea water and melting of glaciers and ice sheets. Another factor that influences sea level variations is land water storage. Regional sea level change is influenced by large-scale ocean circulation patterns, and geologic processes and deformation from the redistribution of ice and water. Local sea level rise is further influenced by vertical land motion from geologic processes, ground water withdrawal, and fossil fuel extraction.

The IPCC AR6 estimates that global mean sea level increased by 7.9 (5.9–9.8) inches between 1901 and 2018. The rate of sea level rise has accelerated in recent decades. At the ocean basin scale, sea levels have risen fastest in the Western Pacific and slowest in the Eastern Pacific over the period 1993–2018. The rate of global sea level rise is estimated to be 0.12 inches/year (for reference: 0.12 in is the height of two stacked pennies).

The observing systems for global sea level rise have advanced significantly in the satellite era, particularly with the advent of satellite altimeters since 1993. Local tide gauges have provided useful data for the past century, and even longer for a few locations. Following the end of the Little Ice Age in the mid-nineteenth century, tide gauges show that the global mean sea level began rising during the period 1820–1860.

### 9.1. U.S. coastal sea level rise

Observed and predicted rates of mean global sea level rise may have little relevance for specific locations. In Canada and Alaska (and also northern Washington), sea level is actually decreasing, owing to uplift from glacial rebound. Most of the Pacific coast has rates of sea level rise of 0 to 0.12 inches/year. The largest rates of sea level rise are on the Gulf coast (Louisiana and Texas) and in the mid-Atlantic states (Chesapeake Bay region).

Measurements of relative sea level rise from tide gauges conflate the rise in the volume of seawater with local vertical land motion. Hence in examining local sea level changes, it is important to also consider the local vertical land motion. Absolute local sea level rise is the sum of relative sea level rise and the local vertical land motion.

A wide range of processes can cause vertical land motion along the coasts, having amplitudes comparable to the sea level signals expected from land-ice melting or ocean thermal expansion. Vertical land motion on the coasts can locally exacerbate (subsidence/sinking) or mitigate (uplift) the risk of sea level rise. Local changes in sea level vary considerably from place to place and can deviate substantially from the rate of global mean sea level change. Human activities triggering subsidence are soil drainage (e.g. for urban development purposes) or subsurface mining of resources such as groundwater, oil or gas. The magnitude of relative sea level rise caused by human activities is often considerable. Local vertical land motion of relevance to local sea level change is best measured using a Global Positioning System (GPS) station located in the location as the tide gauge.

Table 8.1 shows absolute sea-level rise (ASLR) for selected locations, determined from the sum of uncorrected sea-level rise as estimated from tide gauge time series (RSLR) and the vertical land motion (VLM) measurements. The absolute sea level rise for each of these locations is significantly smaller than the measured relative sea level rise owing to local sinking of the land. More than half of the measured relative sea level rise is attributed to land sinking for these locations: San Francisco, Galveston, Grand Isle. For reference, the global average rate of absolute sea level rise is estimated to be 0.12 inches/year.

Table 8.1 Absolute sea level rise (inches/year) (RSLR plus VLM)

| Location          | RSLR  | VLM   | ASLR  |
|-------------------|-------|-------|-------|
| San Francisco, CA | +0.08 | -0.06 | +0.02 |
| Galveston, TX     | +0.26 | -0.19 | +0.07 |
| Grand Isle, LA    | +0.36 | -0.28 | +0.08 |
| St Petersburg, FL | +0.12 | -0.02 | +0.10 |
| New York City, NY | +0.11 | -0.05 | +0.06 |

#### San Francisco Bay

Over the past 100 years, relative sea level in the San Francisco Bay area has risen by 7.8 inches, at an average rate of 0.08 inches/year (Figure 8.1). As shown in Table 6.1, San Francisco's vertical land motion is -0.06 inches/year (sinking), producing a recent rate of absolute sea level rise of +0.02 inches/year. Portions of Treasure Island, San Francisco International Airport, and Foster City are sinking as fast as 0.4 inches/year. Landfill zones are sinking due to soil compaction, at a rate as much as one-half inch per year, threatening coastal infrastructure including the San Francisco International Airport. The problems in the San Francisco Bay area have been caused primarily by sinking in landfill regions that were formerly wetlands, not by the slow creep of global sea level rise.

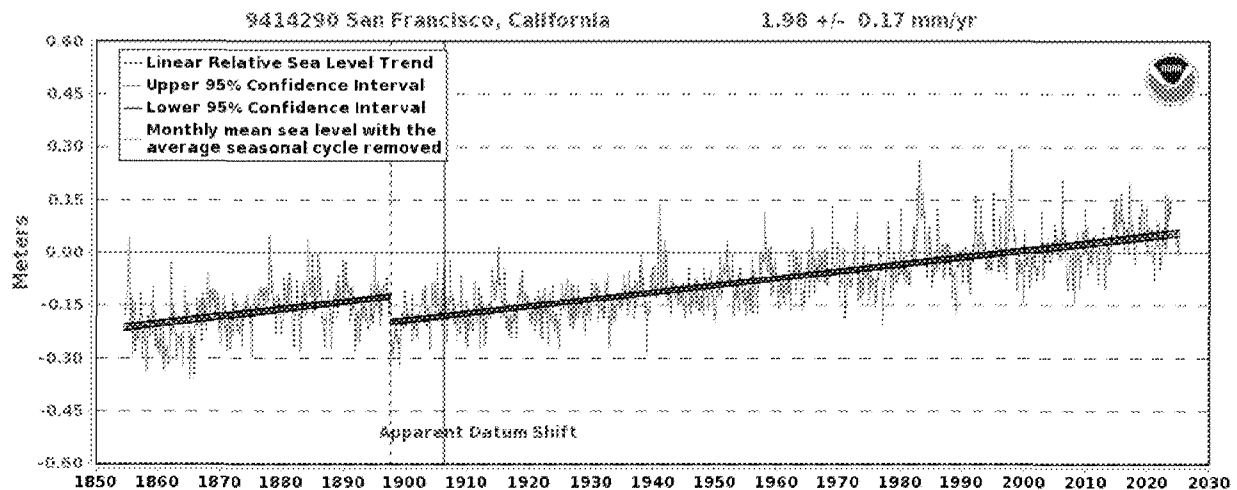
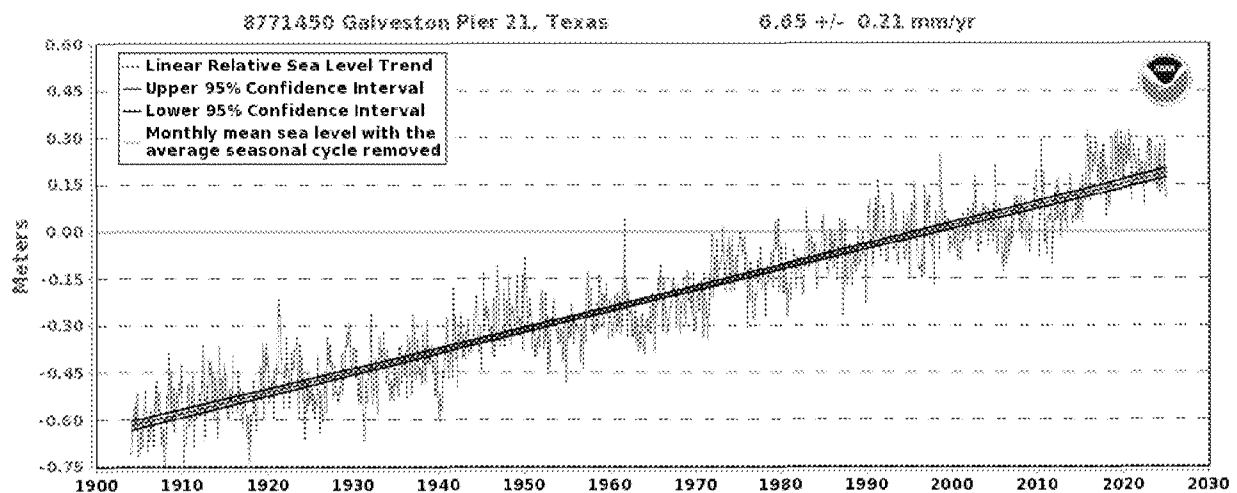


Figure 8.1. Tide gauge measurements at San Francisco, California, obtained from NOAA - [https://tidesandcurrents.noaa.gov/sltrends/sltrends\\_station.shtml?id=9414290](https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=9414290) (downloaded 4/22/25).

#### Galveston - Houston

Long-term tide measurements at Galveston Pier 21 show sea level rise of 2.18 feet in the past century, or a rate of 0.26 inches/year (Figure 8.2). Vertical land motion (subsidence) at Galveston is estimated at -0.19 inches/year, yielding a value of absolute sea level rise of +0.07 inches/year (Table 8.1). The U.S. Geologic Survey found that most of the land-surface subsidence in the Houston-Galveston region has occurred as a direct result of groundwater withdrawals.<sup>6</sup> This caused compaction of the aquifer sediments, mostly in the fine-grained silt and clay layers. By 1979, as much as 10 feet of subsidence had occurred in Houston.

Hurricanes are traditionally the major concern in the region. The 1900 hurricane that struck Galveston and killed between 6,000 and 12,000 people is still considered the United States' deadliest natural disaster.<sup>7</sup> Hurricane Ike (2008) decimated large portions of the Bolivar Peninsula literally removing significant portions of the land mass.<sup>8</sup> While only 17 people were killed in Texas, property damage exceeded \$50 billion.<sup>9</sup> In 2017, Hurricane Harvey struck the region, bringing catastrophic rainfall-triggered flooding that inflicted over \$125 billion in damages.<sup>10</sup>



**Figure 8.2.** Tide gauge measurements Galveston Pier, TX, obtained from NOAA - [https://tidesandcurrents.noaa.gov/sltrends/sltrends\\_station.shtml?id=8771450](https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8771450) (downloaded 4/22/2025).

## New Orleans and the Mississippi delta

<sup>6</sup> Kasmarek, M.C., and Ramage, J.K., 2017, Water-level altitudes 2017 and water-level changes in the Chicot, Evangeline, and Jasper aquifers and compaction 1973–2016 in the Chicot and Evangeline aquifers, Houston-Galveston region, Texas: U.S. Geological Survey Scientific Investigations Report 2017–5080, 32 p., <https://doi.org/10.3133/sir20175080>.

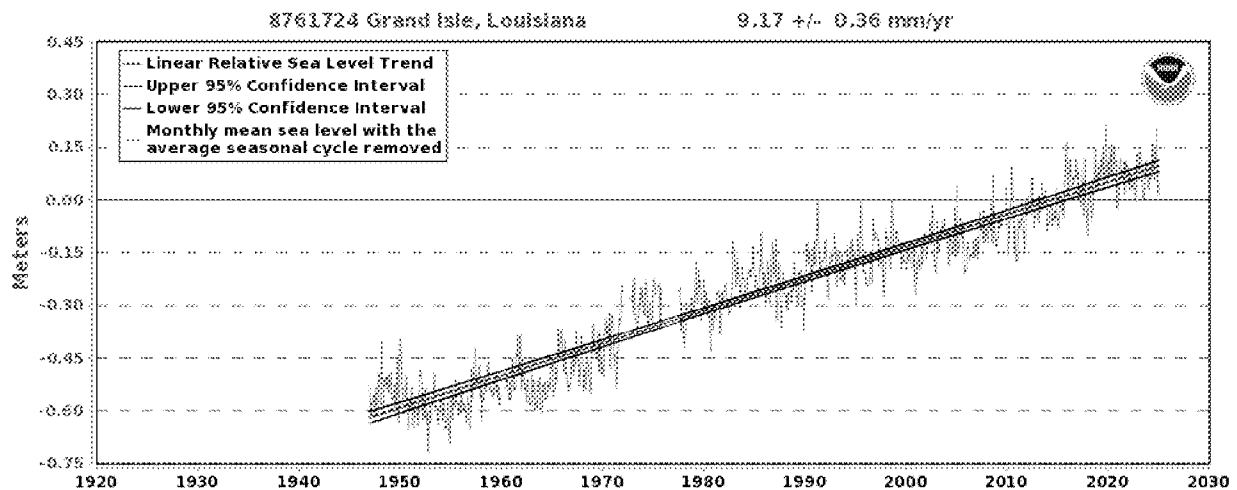
<sup>7</sup> Weems, John Edward, "Galveston Hurricane of 1900", Texas State Historical Association, (March 15, 2016) <https://www.tshaonline.org/handbook/entries/galveston-hurricane-of-1900>.

<sup>8</sup> "Galveston County, Texas, Faces Sea Level Rise and Storms", Union of Concerned Scientists, (June 23, 2017) <https://www.ucs.org/resources/galveston-county-texas-faces-sea-level-rise-and-storms>.

<sup>9</sup> White, Audrey, "Galveston Still Healing 5 Years After Hurricane Ike", The Texas Tribune, (April 26, 2013) <https://www.texastribune.org/2013/04/26/galveston-still-healing-5-years-after-hurricane-ike/>.

<sup>10</sup> NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2025). <https://www.ncei.noaa.gov/access/billions/>, DOI: 10.25921/stkw-7w73

There are long-term tide gauge measurements at Grand Isle, Louisiana, respectively estimating that sea level has risen slightly more than 3 feet over the last 100 years and at an average rate of 0.36 inches/year (Figure 8.3). Vertical land motion (subsidence) is estimated -0.28 inches/year at Grand Isle. From Table 6.1, the absolute sea level rise is +0.08 inches/year at Grand Isle.



**Figure 8.3.** Tide gauge measurements at Grand Isle, LA, obtained from NOAA - [https://tidesandcurrents.noaa.gov/sltrends/sltrends\\_station.shtml?id=8761724](https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8761724) (downloaded 4/22/25).

The issues of sea level rise and land loss in the Mississippi delta region are complex, with geological subsidence and the decline in sediment transported by the Mississippi river being the dominant drivers. Due to the construction of dams in the basin since the 1950s, the suspended sediment load of the Mississippi River has decreased by ~50%.<sup>11</sup> A new subsidence map of coastal Louisiana finds the coastal region to be sinking at about one third of an inch per year.<sup>12</sup> For a city whose elevation averages one to two feet below sea level, sea level rise from human caused warming is not the dominant driver for the problems that New Orleans is facing.

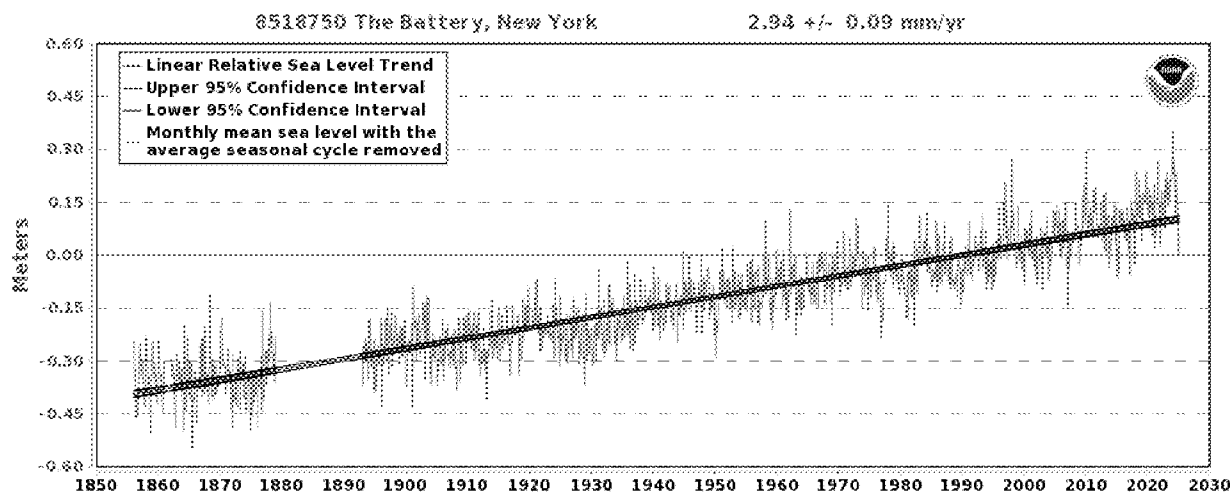
## New York City

New York City is particularly vulnerable to the effects of sea level rise because it is built primarily on islands and has 520 miles of coastline. In New York City, relative sea level has risen over 11 inches over the past century, at an average rate of 0.11 inches/year (Figure 8.4). Vertical land motion in the New York City area is occurring at a rate of -0.05 inches/year (subsidence), corresponding to roughly 5 inches per century. From Table 6.1, the absolute rate of sea level rise at The Battery location is 0.06 inches/year, or about 55% of the measured relative sea level rise.

<sup>11</sup> Jillian M. Maloney et al., "Mississippi River Subaqueous Delta Is Entering a Stage of Retrogradation," *Marine Geology* 400 (June 2018): 12–23, <https://doi.org/10.1016/j.margeo.2018.03.001>.

<sup>12</sup> Jaap H. Nienhuis et al., "A New Subsidence Map for Coastal Louisiana," *GSA Today* 27, no. 6 (June 2017): 28–29, <https://doi.org/10.1130/GSATG337GW.1>.





**Figure 8.4.** Tide gauge measurements at The Battery, New York, obtained from NOAA - [https://tidesandcurrents.noaa.gov/sltrends/sltrends\\_station.shtml?id=8518750](https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8518750) (downloaded 4/22/25).

Following Hurricane Sandy, New York has developed a comprehensive plan: *City of New York: Building a Stronger, More Resilient New York*.<sup>13</sup> A broad range of coastal protection measures are outlined that match the risks facing a given area: increase coastal edge elevations, minimize upland wave zones, infrastructure to protect against storm surge, improve coastal design and governance, restore estuaries wetlands, coastal nourishment, site elevation, and drainage systems.

## 9.2. Sea level rise projections

The concern over sea level rise is not about the 8 inches or so that global mean sea level has risen since 1900. Rather, the concern is about projections of 21st century sea level rise based on climate model-based projections of human-caused global warming.

The IPCC AR6 finds that there is high agreement across published global mean sea level projections for 2050 and there is little sensitivity to emissions scenarios. Considering only projections incorporating ice-sheet processes in whose quantification there is at least medium confidence, the global sea level projections for 2050, across all emissions scenarios, fall between 3.94 and 15.75 inches (5th–95th percentile very likely range) relative to the 1995–2014 baseline period.

Conversely, there is low agreement across published global mean sea level projections for 2100, particularly for higher emissions scenarios. Considering only projections representing processes in whose quantification there is at least medium confidence, the AR6 global mean sea level projections for 2100 lie between 7.87 and 39.37 inches (5th–95th percentile very likely range) under the medium emissions scenario SSP2–4.5. There is deep uncertainty surrounding projections of sea level rise to 2100, particularly for the higher emissions scenarios.

<sup>13</sup> City of New York, *A Stronger, More Resilient New York* (New York: City of New York, June 2013), [http://s-media.nyc.gov/agencies/sirr/SIRR\\_singles\\_Hi\\_res.pdf](http://s-media.nyc.gov/agencies/sirr/SIRR_singles_Hi_res.pdf).

In evaluating the IPCC AR6 projections to 2050 (with reference to the baseline period 1995-2014), almost half of the sea level rise has already occurred by 2025. From the tide gauge measurements in Figures 8.1-8.4, there is no obvious acceleration in sea level rise beyond the historical average rate of sea level rise.

### **9.3. Summary**

Since 1900, global sea level has risen by about 8". Sea level change along U.S. coasts is highly variable, associated with local variations in processes that contribute to sinking and also ocean circulation patterns. The highest levels of sea level rise along U.S. coasts are Galveston, New Orleans, and the Chesapeake Bay regions — each of these locations is associated with substantial local sinking that is unrelated to climate change.

Extreme projections of global sea level rise are associated with the implausible extreme emissions scenario and inclusion of poorly understood processes associated with hypothesized ice sheet instabilities. In evaluating the IPCC AR6 projections to 2050 (with reference to the baseline period 1995-2014), almost half of the sea level rise has already occurred by 2025 and at a lower rate than predicted. From the tide gauge measurements in Figures 8.1-8.4, there is no obvious acceleration in sea level rise beyond the historical average rate of sea level rise.

## Part III: Impacts on Ecosystems and Society

## 10. Climate change and US agriculture

### 10.1. Econometric analyses

Econometric analyses of the effects of climate change on agriculture have sought to integrate information about long term crop yield changes in response to temperature and precipitation changes under assumptions about adaptive behavior by farmers. One method focuses on variations in agricultural land values. The rationale is that if climate change is a long-term net benefit for agriculture it should translate into higher market values for agricultural land, and vice versa. While individual crops might benefit from or be harmed by climate change, once the adaptive responses of farmers are taken into account the value of farmland represents an index of whether the changes are expected to be beneficial or not. Mendelsohn et al. (1994) examined the relationship between historical climatic variations on agricultural land values and concluded global warming would be slightly beneficial to American agriculture.

The Mendelsohn et al. method, called Ricardian analysis after David Ricardo, the 19<sup>th</sup> century British economist who pioneered the study of land values, attracted subsequent criticism from authors who argued it failed to account for differences in land values attributable to fixed locational characteristics like soil quality, and non-climatic changes including nearby urbanization. Deschênes and Greenstone (2007) looked at agricultural profits instead of land values and reached similar conclusions to Mendelsohn et al. (1994), namely that past climatic variations had relatively little effect on farm profitability and that warming would likely yield small overall benefits for the US agricultural sector. However a subsequent exchange with critics led them (Deschênes and Greenstone 2012) to revise their conclusions and project potentially large losses in US agriculture due to climate warming. Burke and Emerick (2016) looked at temperature variations over 1980 to 2000 and argued that farmers were not as able to adapt to temperature changes as the Ricardian method assumes and that climate change would have large negative impacts on corn and soy yields. Schlenker and Roberts (2009) similarly argued that yield gains to past warming would not carry over to the future and corn and soy yields would sharply decrease this century due to climate change.

Two recent studies have argued that pessimistic findings such as these are not robust. Ortiz-Bobea (2019) argued that land values aggregate farm and non-farm influences and the latter need to be filtered out. He developed a data set using cash rents for agricultural activity as a measure of land value specifically for farming activity. Whereas the land value model implied future losses under climate warming, the same model estimated using cash rents did not, leading the author to conclude the pessimistic results were due to using an inaccurate measure of the returns to farming activity. Bareille and Chakir (2023) assembled a large data base on farm sale prices in France for properties that sold twice between 1996 and 2019. They could replicate pessimistic results showing negative effects of warming on agricultural land values using conventional econometric modeling. But by taking advantage of the repeat sales data, which provides information on site-specific changes in land prices, they found the results reversed and implied that climate change will be very beneficial for French agriculture. The authors concluded that, taking adaptation into account, a warming climate would yield positive benefits for French agriculture that were between two and 20 times larger than had previously been estimated.

On average, with full adaptation, they concluded that climate changes under the medium RCP4.5 scenario could double the value of French farmland by 2100.

A major deficiency of all these studies, however, is that they omit the role of CO<sub>2</sub> fertilization. Climate change as it relates to this report is caused by GHG emissions, chiefly CO<sub>2</sub>. The econometric analyses referenced above focus only on temperature and precipitation changes and do not take account of the beneficial growth effect of the additional CO<sub>2</sub> that drives them. As explained in Chapter 2 CO<sub>2</sub> is a major driver of plant growth so this omission biases the analysis towards underestimation of the benefits of climate change on agriculture.

## **10.2. Field studies of CO<sub>2</sub> enrichment**

One of the ways the effect of CO<sub>2</sub> on crop growth has been studied is through “free air enrichment experiment” or FACE plots, in which small chimneys are placed in fields surrounding plants and the growth response to elevated CO<sub>2</sub> under varying weather conditions are recorded. Ainsworth et al. (2020) summarizes results from about 250 such studies. They found that elevation of CO<sub>2</sub> by 200 ppm cause an average 18% increase in crop yield in C3 plants. C4 plants exhibited benefits mainly under drought conditions.

In addition to FACE plot experiments there have been thousands of laboratory experiments on the effects of CO<sub>2</sub> on all kinds of plant growth. Here we review some of the results on key US agricultural crops.

### **Soybean**

Studies on the impact of elevated CO<sub>2</sub> on Soybean (*Glycine max* (L.) Merr.) plants in the water-deficient region of Huang-Huai-Hai Plain, China, showed that elevated CO<sub>2</sub> concentrations resulted in improved photosynthesis rate, water use efficiency and growth (Li, 2013) under both normal conditions and drought conditions. The CO2Science.org website reports on 108 published experiments between 1985 and 2019 exposing soybean to enriched CO<sub>2</sub> levels. Converted to a +300ppm common scale the average growth benefit was +50.9 percent. In addition there were 10 studies reporting on +600 ppm CO<sub>2</sub> enrichment, resulting in an average increase in photosynthesis of 90.3%.

### **Maize (corn)**

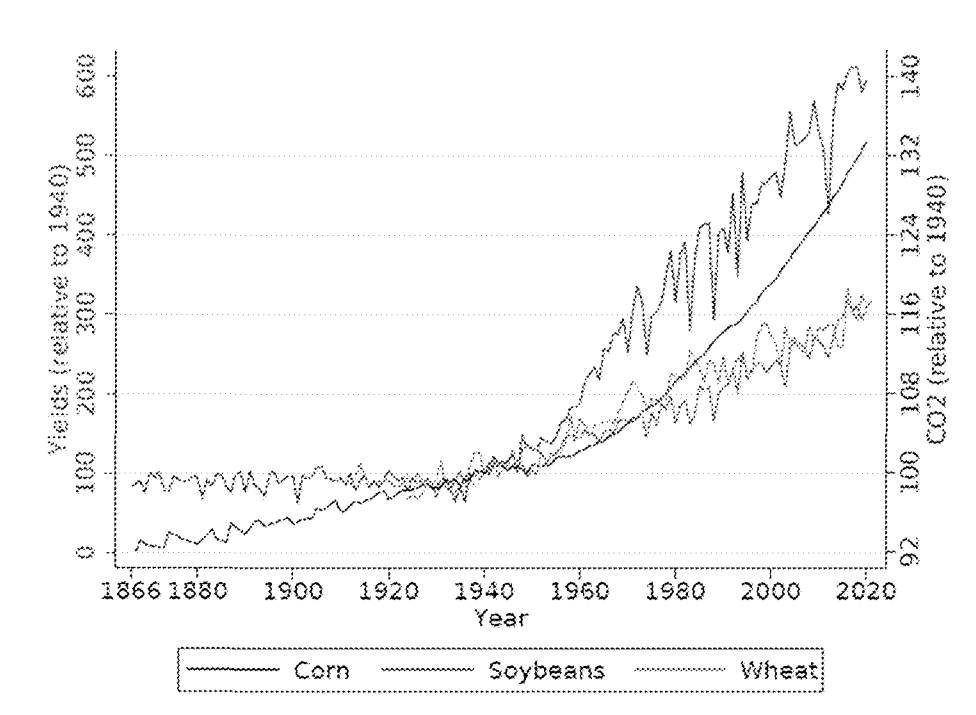
The CO2Science.org website reports on 28 published experiments between 1983 and 2018 exposing corn (*Zea mays* L.) to enriched CO<sub>2</sub> levels. Converted to a +300ppm common scale the average growth benefit was +23.7 percent. Corn also benefits from increased drought tolerance under elevated CO<sub>2</sub>. An experimental study (Allen Jr, 2011) exposed plants to water stress conditions in sunlit controlled-environment chambers at 360 ppm (ambient) and 720 ppm (elevated) CO<sub>2</sub>. The drought stress caused a 41% loss of growth under ambient CO<sub>2</sub> but only a 13% loss under elevated CO<sub>2</sub>.

## Wheat

The CO2Science.org website reports on 92 published experiments between 1983 and 2020 exposing common wheat (*Triticum aestivum* L.) to enriched CO<sub>2</sub> levels. Converted to a +300ppm common scale the average growth benefit was +67.6 percent. Blandino (2020) measured the yield as well as nutritional quality of an “improver” hybrid wheat variety and its parents under elevated CO<sub>2</sub> levels (+166 ppm). They reported a grain yield increase of +16% but a 7% decrease in grain protein levels. But they found that the food quality of different wheat varieties responded differently to elevated CO<sub>2</sub> levels, so that with proper varietal selection end-users can select wheat types that best take advantage of the elevated CO<sub>2</sub>.

## Further evidence

A 2021 report from the US National Bureau of Economic Research (Taylor and Schlenker 2021) used satellite-measured observations of outdoor CO<sub>2</sub> levels across the United States, matched to county-level agricultural output data and other economic variables. After controlling for the effects of weather, pollution and technology the authors concluded that CO<sub>2</sub> emissions had boosted US crop production since 1940 by 50 to 80 percent, attributing much larger gains than had previously been estimated using FACE experiments. They found that every ppm of increase in CO<sub>2</sub> concentration boosts corn yields by 0.5 percent, soybeans by 0.6 percent, and wheat by 0.8 percent.



**Figure 10.1:** US average CO<sub>2</sub> levels and yields of corn, soy and wheat all normalized so 1940=100. Source: Taylor and Schlenker (2021)

Beyond growth benefits, extra CO<sub>2</sub> boosts plant resilience to heat. Deryng et al. (2016) surveyed all available evidence regarding how wheat, maize, rice and soybean will grow under a combination of climate warming and rising CO<sub>2</sub> levels. They concluded that warming would, eventually, have a negative effect on plant growth but it would be fully compensated by the extra CO<sub>2</sub> for wheat and soybean, and almost fully for rice and maize. And as discussed in Chapter 2, plants use water more efficiently when there is more CO<sub>2</sub> in the air.

Deryng et al. (2016) surveyed evidence on crop water productivity (CWP), i.e. yield per unit of water used, drawing attention to the potential for CO<sub>2</sub> both to enhance photosynthesis and reduce leaf-level transpiration (water loss during leaf respiration). They surveyed all available FACE data on crop yield changes for Maize (corn), Wheat, Rice and Soybean, and combined it with crop model data simulating yield responses as of 2080 under the extreme RCP8.5 scenario in four growing regions (Tropics, Arid, Temperate and Cold) each of which were split into rainfed and irrigated sub-regions. In every region they reported that models without CO<sub>2</sub> fertilization predicted CWP losses but CO<sub>2</sub> fertilization more than offset them and once it was taken into account all regions showed a net CWP gain. Deryng et al (2016) also reported that negative impacts on wheat and soybean yields were fully offset by CWP gains, and mitigated by up to 90% for rice and 60% for maize.

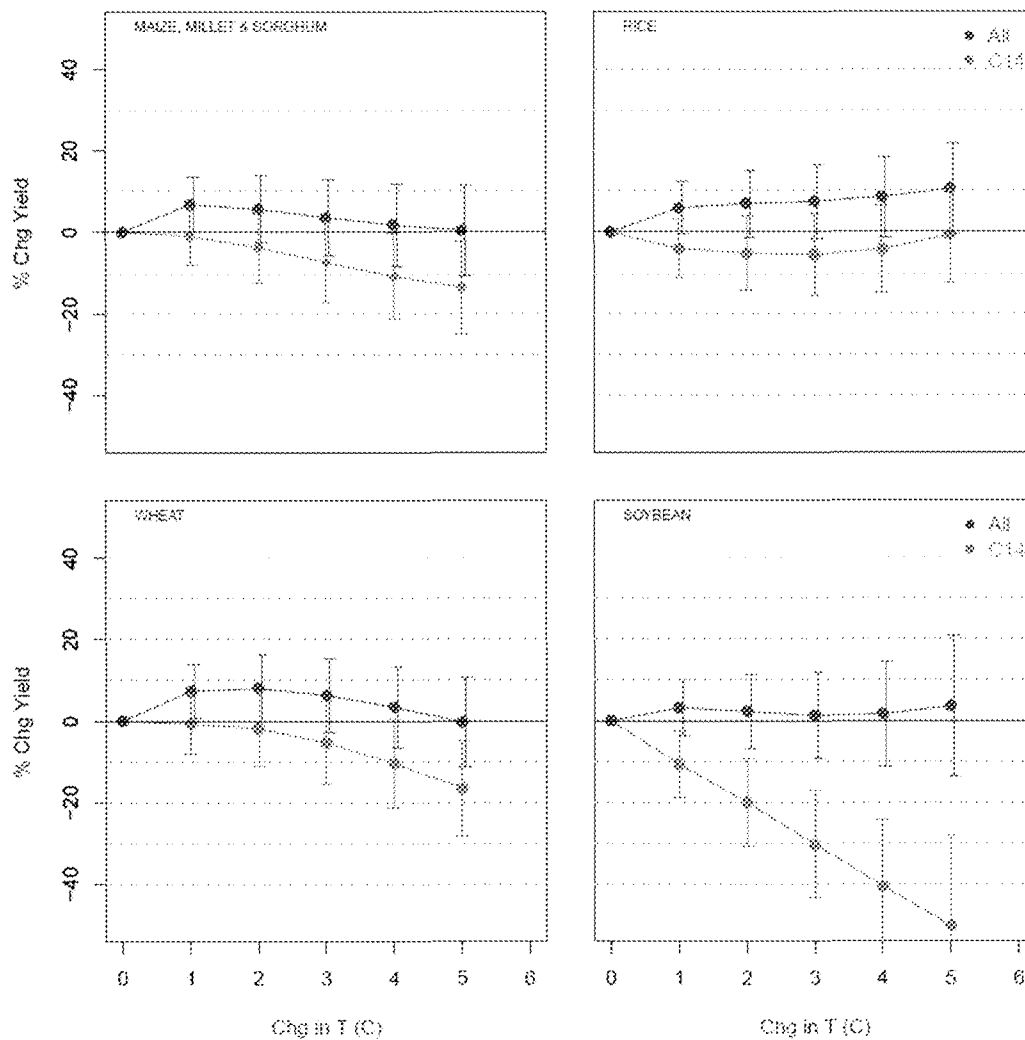
Similar to this, Cheng et al. (2017) noted that increased global plant growth from 1982 to 2011 due to rising CO<sub>2</sub> uptake was accompanied by such large gains in CWP that despite the extra biomass global water use by plants had not increased.

Deryng et al. (2016) assumed that climate change would “exacerbate water scarcity”. It is noteworthy that while models predict drylands will expand under climate warming, current data show the opposite: greening is happening even in arid areas. Zhang et al. (2014) report that due to increased CO<sub>2</sub> levels “increasing aridity in drylands won’t lead to a general loss of vegetation productivity”; increased desertification will happen in at most 4% of currently arid areas.

### **10.3. Crop modeling meta-analyses**

Notwithstanding the abundant evidence for the direct benefits of CO<sub>2</sub> and of CO<sub>2</sub>-induced warming on crop growth, in 2023 the US Environmental Protection Agency (EPA 2023) boosted its estimate of the Social Cost of Carbon (SCC) about five-fold based in large part on a very pessimistic 2017 estimate of global agricultural damages from climate warming (Moore et al., 2017). One of the two damage models used by the EPA attributed nearly half of the 2030 SCC to projected global agricultural damages based on the Moore et al. (2017) analysis. This study was a meta-analysis of crop model studies simulating yield changes for agricultural crops under various climate warming scenarios. Moore et al. projected declining global crop yields for all crop types in all regions due to warming.

McKittrick (2025) re-examined the Moore et al. database and found that, while it claimed to cover 1,722 studies, only half the entries ( $N=862$ ) had complete records, so that the sample available for regression analysis was much smaller than both studies indicated. McKittrick noted that the variable most commonly missing was the change in ambient  $\text{CO}_2$  and found that in many cases these could be recovered from the underlying studies or the original climate scenario tables. He thereby increased the usable sample size by 40 percent. The crop yield projections incorporating the newly available data changed considerably. As shown in Figure 10.2, whereas the partial data set implied warming would decrease yield (blue lines), the complete data set implied constant or increase global yields, even out to  $5^\circ\text{C}$  warming (green lines).



**Figure 10.2** Crop yields under  $\text{CO}_2$ -induced climate warming. Blue: as published in Moore et al. (2017). Green: after including omitted data. Source: McKittrick (2025).



In summary, there is abundant evidence going back decades that rising CO<sub>2</sub> levels benefit plants including agricultural crops, and that CO<sub>2</sub>-induced warming will be a net benefit to US agriculture. The warming since 1981, in combination with adaptive behaviour by farmers, has been beneficial on its own for maize. The increased ambient CO<sub>2</sub> has also boosted productivity of all major US crop types. Various attempts to argue that CO<sub>2</sub>-induced warming will harm agriculture do not hold up under scrutiny.

Deschênes, Olivier and Michael Greenstone (2007) The Economic Impacts of Climate Change: Evidence from Agricultural Output and Random Fluctuations in Weather *American Economic Review*. Feb 2007, Vol. 97, No. 1: Pages 354-385

Deschênes, Olivier and Michael Greenstone (2012) The Economic Impacts of Climate Change: Evidence from Agricultural Output and Random Fluctuations in Weather: Reply to Comment *American Economic Review*. 102, no. 7: 3761-3773. <http://hdl.handle.net/1721.1/82641>

Ortiz-Bobea, Ariel (2019) The role of nonfarm influences in ricardian estimates of climate change impacts on US agriculture. *American Journal of Agricultural Economics*. 102 (3), 934–959.

Schlenker, Wolfram and Michael Roberts (2009) Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. *Proceedings of the National Academy of Sciences* 106 (37) 15594-15598 <https://doi.org/10.1073/pnas.0906865106>

# 11. Managing risks of extreme weather

## 11.1. Socioeconomic context

Risks from human-caused climate change are convoluted with natural weather and climate variability, and are dominated by the exposure of wealth in coastal and other disaster-prone regions and vulnerabilities of poorer populations. The evolution of climate risk in the U.S. has been dominated by societal factors, rather than by changes to the actual weather and climate hazards. Deaths from weather disasters have decreased substantially since 1900, even as US population grew from 76 million in 1900 to over 331 million in 2020. For example, the Galveston hurricane killed over 8,000 people in 1900 (0.01% of the US population), whereas the worst recent disaster, Hurricane Katrina in 2005, killed 1800 people (or 0.0006% of the US population).

Technological advances have substantially reduced losses from extreme weather events. Early warning systems, satellite monitoring, and improved weather forecasting have reduced deaths, although exact numbers are hard to quantify. <https://www.nber.org/papers/w31361>

US weather forecasting has been estimated to reduce losses from weather events with an annualized benefit of \$31.5B, protecting lives, property, and supporting agriculture and transportation <https://nap.nationalacademies.org/read/12888/chapter/2> Improved hurricane forecasts have reduced pre- and post-landfall spending, with annual per hurricane cost reductions estimated at \$5B

<https://www.nber.org/digest/202409/value-improving-hurricane-forecasts>

Infrastructure improvements have contributed to substantial reductions in losses from extreme weather events. Building codes, such as those implemented in Florida after Hurricane Andrew (1992) have reduced losses by ensuring structures can withstand high winds and floods. Homes built after 2002 showed minimal damage during Hurricane Michael (2018), unlike older homes.

<https://www.fema.gov/case-study/role-floridas-building-codes-2018-hurricane-michael>. Sea walls, like the Galveston Seawall, protect against wave action and storm surge. The New Orleans Hurricane and Storm Damage Risk Reduction System successfully mitigated storm surge during Hurricane Isaac (2012). Inland dams in the US help control flooding by storing excess water during heavy rains. It is estimated that the Tennessee Valley Authority (TVA) dams prevent about \$309M in annual flood damage in the TVA region and along the Ohio and Mississippi Rivers <https://www.tva.com/environment/managing-the-river/flood-management>

During Hurricane Helene (2024), TVA's strategies prevented approximately \$406M in potential damages. <https://www.publicpower.org/periodical/article/tva-flood-mitigation-strategies-prevented-approximately-406-million-potential-damages>

## 11.2. Data challenges

Since 1980, NOAA has provided a count of annual U.S. weather-related disasters that it estimates to have exceeded \$1Billion (inflation adjusted), showing a substantial increase starting in 2008. NOAA and other government officials have cited the upward trend in the BDD series as evidence that climate change is making extreme weather worse (Pielke Jr. 2024). But over time, population and wealth have increased dramatically in the US, so when an extreme weather or climate event occurs, there is more damage even if there is no underlying trend in the frequency or intensity of extreme weather. A recent estimate finds that losses per weather disaster are down by about 80% since 1980, as a proportion of GDP.

<https://drive.google.com/file/d/1MvgwcWaimcn1oHODqNZDG1fXF4M5Idnn/view>

Pielke Jr. (2024) argued that in addition to relying on opaque data sources and unreported adjustments NOAA failed to normalize its Billion Dollar Disaster (BDD) data series properly for changes in population exposure and wealth. In May 2025 NOAA announced it has withdrawn the billion dollar disaster product from publication (Pielke Jr. 2025).

In summary, trends in losses from extreme weather and climate events are dominated by population increases and economic growth. Technological advances such as improved weather forecasting and early warning systems have substantially reduced losses from extreme weather events. Better building codes, flood defenses, and disaster response mechanisms have lowered economic losses relative to GDP. And finally, the US economy's expansion has diluted the relative impact of disaster costs, as seen in the comparison of historical and modern GDP percentages.

Pielke Jr., Roger (2024) Scientific integrity and U.S. "Billion Dollar Disasters" *NPJ Natural Hazards* 1  
<https://www.nature.com/articles/s44304-024-00011-0>

Pielke Jr., Roger (2025) "RIP NOAA's Billion Dollar Disasters" Substack essay May 8, 2025  
<https://rogerpielkejr.substack.com/p/rip-noaas-billion-dollar-disasters>

## 12. Mortality from temperature extremes

### 12.1. Heat and cold risks

Changes in temperature extremes are among the most certain impacts expected in a warming globe -- extreme heat events are expected to become more frequent while extreme cold events become less frequent. This pattern is evident in the historical period (as discussed in Section XX) and is expected to intensify with continued warming.

Mortality during heat extremes is typically caused by heat stroke and heat exhaustion, while mortality during cold extremes is typically caused by hypothermia and heart strain. It is well known that global mortality is substantially greater for extreme cold than for extreme heat.<sup>14,15</sup>

Specific to the U.S., extreme heat and extreme cold both kill hundreds of people each year.; however, different approaches to assessing heat/cold mortality produces different results. The Center for Disease Control (CDC) National Center for Health Statistics Compressed Mortality Database, which is based on death certificates, indicates that about twice as many people die of “excessive cold” conditions in a given year than of “excessive heat.”<sup>16,17</sup>

A 2015 epidemiological study of deaths in published in *The Lancet* found that cold-related deaths in the U.S. were about a factor of fifteen higher than heat-related deaths.<sup>18</sup> However, the study did not adjust for the seasonal cycle in mortality rates, which tend to increase during the winter months due to non-weather factors like influenza.<sup>19</sup> A more recent paper found that 86% of temperature-related deaths in the U.S. are due to cold-related mortality.<sup>20</sup>

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<sup>14</sup> Qi Zhao et al., “Global, Regional, and National Burden of Mortality Associated with Non-Optimal Ambient Temperatures from 2000 to 2019: A Three-Stage Modelling Study,” *The Lancet Planetary Health* 5, no. 7 (July 2021), [https://doi.org/10.1016/s2542-5196\(21\)00081-4](https://doi.org/10.1016/s2542-5196(21)00081-4).

<sup>15</sup> <https://ourworldindata.org/part-one-how-many-people-die-from-extreme-temperatures-and-how-could-this-change-in-the-future>

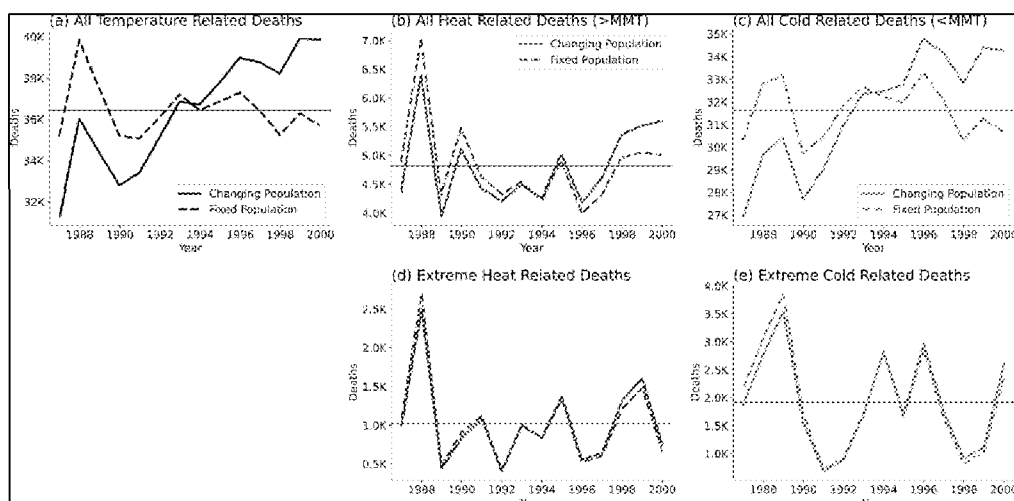
<sup>16</sup> Brett R. Scheffers et al., “The Broad Footprint of Climate Change from Genes to Biomes to People,” *Science* 354, no. 6313 (November 11, 2016): aaf7671, <https://doi.org/10.1126/science.aaf7671>.

<sup>17</sup> Rachel H. Alinsky, Scott E. Hadland, J. Deanna Wilson, Pamela A. Matson, and Brendan Saloner, “Trends in Polysubstance Overdose Deaths Involving Opioids, Stimulants, and Benzodiazepines by Race and Ethnicity in the US, 2007-2021,” *JAMA Network Open* 7, no. 3 (March 2024): e238249, <https://doi.org/10.1001/jamanetworkopen.2024.8249>.

<sup>18</sup> Lancet Commission on Climate and Health, “Health and Climate Change: Policy Responses to Protect Public Health,” *The Lancet* 386, no. 10006 (November 7, 2015): 1861–1914, [https://doi.org/10.1016/S0140-6736\(15\)60854-6](https://doi.org/10.1016/S0140-6736(15)60854-6).

<sup>19</sup> Bob Henson, “Which Kills More People: Extreme Heat or Extreme Cold?” *Weather Underground*, January 22, 2019, <https://www.wunderground.com/cat6/Which-Kills-More-People-Extreme-Heat-or-Extreme-Cold>.

<sup>20</sup> Tarik Benmarhnia et al., “Deaths Attributable to Heat and Cold: Comparison of Data Sources and Evaluation of Inconsistencies,” *GeoHealth* 8, no. 3 (March 2024): e2023GH000799, <https://doi.org/10.1029/2023GH000799>.



**Figure 12.1:** Time series of temperature-related deaths across all 106 cities. (a) The solid line represents total temperature-related deaths, while the dashed line indicates temperature-related deaths with a fixed population (average population from the 1987–2000 period). (b) Similar to (a), but for heat-related deaths. (c) Similar to (a), but for cold-related deaths. (d) Time series of deaths occurring in temperatures above the 97.5th percentile. (e) Similar to (d), but for temperatures below the 2.5th percentile. From <https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2023GH000799>

The IPCC AR6 Working Group 2 Chapter 16.2.3.5 states how heat-related mortality is declining over time:<sup>21</sup>

“Heat-attributable mortality fractions have declined over time in most countries owing to general improvements in health care systems, increasing prevalence of residential air conditioning, and behavioral changes. These factors, which determine the susceptibility of the population to heat, have predominated over the influence of temperature change.”

A 2011 study of 40 major US cities between 1975 and 2004, found that heat wave mortality had decreased, in spite of rising temperatures, due to adaptation.<sup>22</sup> Likewise Davis et al. (2003) examined heat-related mortality in 28 U.S. cities from the 1960s to the end of the 1990s and found that heat-related mortality declined by three-quarters over the sample period. Bobb et al. (2014) examined mortality data for 106 million people in over 100 cities U.S. cities and found a 60% decline in average heat-related mortality over the period 1987–2005, from 51 per thousand deaths to 19. They furthermore found that the greatest drop was among seniors over the age of 75. In a study of 42 million

<sup>21</sup> B. O'Neill et al., “Key Risks Across Sectors and Regions,” in *Climate Change 2022: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Geneva, CH: Intergovernmental Panel on Climate Change, 2021), 2411–2538.

<sup>22</sup> Keith T. Ingram, Carolyn W. Furman, and John W. Jones, “Climate Change Impact and Adaptation Assessment: A Guide for Coastal Resources Managers,” *Weather, Climate, and Society* 3, no. 4 (October 2011): 234–249, <https://doi.org/10.1175/WCAS-D-11-00055.1>.

deaths in 211 U.S. cities from 1962 to 2006. Nordio et al. (2015) found a more than 90 percent decline in the risk of mortality from excess heat.

In the context of large declines in heat-related mortality, by reducing mortality from cold events rising temperatures are associated with a net saving of lives.

It is both disappointing and telling to see how the IPCC misrepresents the situation in its AR6 Synthesis report. Section A.2.5 of that document states: “In all regions increases in extreme heat events have resulted in human mortality and morbidity (*very high confidence*).” But it is silent on the larger decline of deaths during extreme cold events.

## **12.2. The importance of adaptation**

The observed decline in US heat-related mortality has been specifically attributed to adaptation. Wang et al. (2018) exploited the spatial variability of heatwave-related mortality across 209 U.S. cities from 1962 to 2006. While simple correlation appeared to imply an increase in mortality risk during heatwaves, accounting for adaptation to heatwave intensity caused the effect to fall to near zero and become statistically insignificant. They used the results of their epidemiological model to project heat-related mortality out to 2050 under four RCP warming scenarios (including RCP8.5) with and without adaptive behavior. Assuming people continue to adapt to the heatwave risks in the regions in which they live Wang et al. project not only no increase in heat-related mortality but an overall decrease for the US as a whole. They conclude that “Ignoring adaptation would result in a substantial overestimate of future mortality related to heat waves... Accounting for adaptation, the overall heat-related mortality by 2050 would not change substantially over time compared to 2006.”

## **12.3. Mortality risks and energy costs**

A 2016 study of US long term mortality risks associated with temperature variations (Barreca et al. 2016 ) showed that increases in mortality across the US are associated both with cold weather and hot weather. But over time, the introduction of electricity and the adoption of central heating and air conditioning (AC) dramatically reduced both risks, especially those associated with hot weather. Prior to 1960, a day above 90°F (32°C) added 2.2 percent to the average mortality risk rate, but after 1960 the same weather added only 0.3 percent to mortality risk, an 85 percent reduction. Prior to 1960 temperatures below 39°F (4°C) added about 1 percent to mortality risk but after 1960 the same weather only added about half that amount. Adaptation through conventional household improvements dramatically reduced public vulnerability to weather extremes. The entire reduction in hot weather mortality was attributable to widespread adoption of indoor AC, which depended on the availability of reliable and affordable electricity.

The corollary of this finding is that the use of heating and cooling systems depends on energy being affordable. Doremus et al. (2022) showed that wealthy and poor households in the US adjust their energy expenditures at similar rates in response to moderate temperature swings, but not in response to extreme temperature swings. When temperatures swing to very cold levels (< 5°C) energy spending in high-income households rises by 1.2 percent but in low-income households by only 0.5 percent. On very

hot days (>30°C) electricity spending in high-income households rises by 0.5 percent but does not change at all in low-income households. The latter result is observed even in subsamples where all households have AC. The implication is that even with widespread adoption of home heating and cooling systems, inability to afford energy leaves low-income households exposed to weather extremes.

Barreca, Alan, Karen Clay, Olivier Deschenes, Michael Greenstone, and Joseph S Shapiro, “Adapting to climate change: The remarkable decline in the US temperature mortality relationship over the twentieth century,” *Journal of Political Economy*, 2016, 124 (1), 105–159.

J.M. Doremus, I. Jacqz and S. Johnston (2022), “Sweating the energy bill: Extreme weather, poor households, and the energy spending gap.” *Journal of Environmental Economics and Management*, doi: <https://doi.org/10.1016/j.jeem.2022.102609> .

Nordio, Francesco, Antonella Zanobetti, Elena Colicino, Itai Kloog and Joel Schwartz (2015). “Changing patterns of the temperature–mortality association by time and location in the US, and implications for climate change” *Environment International*, Volume 81, pp 80-86  
<https://doi.org/10.1016/j.envint.2015.04.009>.

Wang, Yan, Francesco Nordio , John Nairn , Antonella Zanobetti and Joel D. Schwartz (2018) “Accounting for adaptation and intensity in projecting heat wave-related mortality” *Environmental Research* 161 pp. 464—471. <https://doi.org/10.1016/j.envres.2017.11.049>

Bobb JF, Peng RD, Bell ML, Dominici F. (2014) Heat-related mortality and adaptation to heat in the United States. *Environmental Health Perspectives* 122:811–816;  
<https://ehp.niehs.nih.gov/doi/full/10.1289/ehp.1307392>

Davis, Robert E., Paul C. Knappenberger, Patrick J. Michaels and Wendy M. Novicoff (2003) “Changing Heat-Related Mortality in the United States” *Environmental Health Perspectives* 111(14) November 2003 pp. 1712—1718.

# 13. Climate change, the economy and the Social Cost of Carbon

## 13.1. Climate change and economic growth

### 13.1.1 Overview: climate is a relatively minor issue for a modern economy

It has long been noted that economies tend to do poorly in very cold and very hot regions, with the optimum somewhere in between (Nordhaus 2006). Temperature-sensitive economic activity migrates, whenever possible, to where it is best suited, and society always adapts to the local climate. Based in part on these observations, in 1992 Thomas Schelling, then President of the American Economic Association, argued that any effects climate change on US economic activity would be small relative to the many other changes that would happen.

... Manufacturing rarely depends on climate, and where temperature and humidity used to make a difference, air conditioning has intervened. When Toyota chooses among Ohio, Alabama, and Southern California for locating an automobile assembly, geographical considerations are important, but not because of climate... Finance is little affected by climate; similarly for health care, or education, or broadcasting. Transportation can be affected, but improvements in all-weather landing and take-off in the last 30 years are greater than any differences that climate makes. If the average effect is a warming, iced waterways and snow removal may decline in importance. Construction is affected, mainly by cold, and if the average effect is in the direction of warming, construction may benefit slightly.

It is really agriculture that is affected. But even if agricultural productivity declined by a third over the next half century, the per capita GNP we might have achieved by 2050 we would achieve only in 2051. ...

**I conclude that in the United States, and probably Japan, Western Europe, and other developed countries, the impact on economic output will be negligible and unlikely to be noticed.**

(Schelling 1992, emphasis added)

Thirty years later virtually the identical point was made by the IPCC itself in the Fifth Assessment Report:

**For most economic sectors, the impact of climate change will be small relative to the impacts of other drivers.** Changes in population, age, income, technology, relative prices, lifestyle, regulation, governance, and many other aspects of socioeconomic development will have an impact on the supply and demand of economic goods and services that is large relative to the impact of climate change.



(Arent et al. 2014, emphasis added)

That statement is validated by experience. Since 1900, the average global surface temperature anomaly warmed 1.3°C, about as much as the IPCC predicts will occur in the next century under a moderate emissions scenario. But even as the globe warmed and the population quintupled, humanity prospered as never before. For example, global average lifespan went from thirty-two years to seventy-two years, economic activity per capita grew by a factor of seven, and the death rate from extreme weather events plummeted by a factor of fifty!

While extreme weather events are costly, in all modern economies they are becoming steadily less and less important (Formetta and Feyen 2019). Since 1990 weather-related disaster losses have declined as a proportion of global GDP (Pielke Jr 2018, 2020) as have mortality risks (Formetta and Feyen 2019). While economic weather-related insurance payouts are rising, this is fully explained by the growth in the size of the economy and the value of the insured asset stock. Past increases in episodes extreme weather have not had a significant effect (positive or negative) on the market value of insurance firms (Hu and McKittrick 2015). Nor have past extreme weather events had a significant effect on US banks' performance (Blickle et al. 2021).

For these reasons, economists have long been reluctant to endorse attempts to “stop” climate change or even aggressively reduce GHG emissions because the costs would not be worth it. As one critic of the economics of climate policy put it:

Mainstream climate economics takes global warming seriously, but perplexingly concludes that the optimal economic policy is to almost do nothing about it... The contrast is striking. While climate science is sending out loud-and-clear messages that fossil-fuel disinvestment must start now, letting go of coal and oil and diverting resources into renewable energy technology systems, to keep warming below the 2°C limit (IPCC 2014), mainstream climate economics claims that overly ambitious climate targets will unnecessarily hurt the economy and immediate de-carbonization is too expensive. Most climate economists thus recommend humanity to just wait-and-see.

(Storm 2017)

The mainstream economics position on the climate policy question is best represented by the findings over the past three decades from Integrated Assessment Models (IAMs) of climate change policy, for which Yale economist William Nordhaus was awarded the 2018 Nobel Memorial Prize in economics. IAMs combine economic, climate, and social data into a unified framework for simulating climate damages and evaluating the optimal policy response (Resources for the Future 2025). Nordhaus' work has generally supported modest global climate policy, with aggressive measures largely deferred to later in the century. Nordhaus developed the so-called Dynamic Integrated Model of the Climate and Economy model, or DICE, in the early 1990s (Nordhaus 1993) to study the interaction between climate change, climate policy, and global economic growth over long times. DICE assumes global emission control can be coordinated at no cost and asks what the optimal policy target should be. The climate component of the DICE model is based on simplified climatological modeling. The version of DICE at the

time of Nordhaus' Nobel Prize award was described in Nordhaus (2018); it had a climate sensitivity parameter of 3.1°C for CO<sub>2</sub> doubling, consistent with the best estimate in contemporary IPCC reports (3.0°C).

The baseline (no policy) scenario incurs only \$0.4T in global abatement costs and leads to \$134.2T (trillion dollars) in global climate damages for a total cost of \$134.6T. The climate model component of DICE projects 4.1°C warming by 2100 relative to preindustrial temperatures. Note that this is a higher estimate of warming than many IPCC climate models. (AR6 offers 2.7°C in 2100 under a moderate emissions scenario.)

The Optimal Policy scenario barely deviates from the business-as-usual path. It aims for +3.5°C warming, in other words we scale back only the lowest-value fossil fuel use and otherwise just live with almost all the warming. This suggests that most CO<sub>2</sub> emissions are less harmful than the policies that would be necessary to abate them. Trying to prevent warming causes costs quickly to outstrip the benefits. Pursuing a goal of capping warming at 2.5°C creates total costs of \$177.8T, which is \$43.2T worse than doing nothing at all. Nordhaus didn't evaluate trying to reach a Paris-type target of 1.5°C warming but it would be even worse.

A subsequent edition of DICE includes higher assumed damages from warming which, not surprisingly leads to more aggressive policy recommendations, as explained in the section below on the Social Cost of Carbon.

### **13.1.2 Empirical analysis of climate change and economic growth**

Many other studies have used econometric methods instead of IAMs to look at the potential impact of climate change on economic growth. Dell et al. (2012, herein DJO12) was an influential study that used a multi-country panel of national-level data spanning 1950 to 2005, in which they matched climate and economic data by averaging temperature from the local grid cell level up to the national level using population weights. They found that warming yields an insignificant positive effect on income growth in rich countries but a significant negative effect in poor countries. Moore and Diaz (2015) modified the DICE model to take that finding into account and concluded that it implied a dramatically higher Social Cost of Carbon due to the compounding effects of income loss over time.

A large subsequent literature has debated the robustness of the DJO12 findings. Burke et al. (2015) analyzed a global panel with temperatures averaged up to the national level and found a negative effect on growth from warming in rich and poor countries alike when the national average temperature is above 13°C. Zhao et al. (2018) used the G-Econ data set of Nordhaus (2006), which breaks economic activity down to the grid cell level, replicated DJO12-type results on the same subset of countries as used in DJO12 but then showed that on the full global sample warming increases growth in rich countries and poor countries alike, though the positive effect in the latter group is confined to where local temperatures are below about 16°C. Greßer et al. (2021) developed a regional economic data set for 1,542 sub-national regions around the world between 2005 and 2015 and found temperature had no effect on growth. Yang et al. (2023) updated the DJO12 data set and applied an estimator robust to

mixed sample frequencies, finding that while temperature shocks exerted a temporary effect on income levels, they did not have a significant lasting effect on growth rates.

Newell et al. (2021) noted that there is no underlying theory to guide econometric model specification in this literature. Taking into account the arbitrary choices of which explanatory variables to include they identified over 800 possible model specifications. Using the Burke et al. (2015) data they used an estimation method that accounts for model uncertainty and found that the model form preferred by Burke et al. (2015), which implied negative effects of warming on growth even in rich countries, is explicitly excluded by the optimal model selection algorithm. Overall they could not detect a temperature effect on GDP or GDP growth, and they estimated the 95% confidence interval for the impact on global growth as of 2100 even under the exaggerated RCP8.5 warming scenario spans -86 percent to +388 percent. In other words the net effect is likely positive but too uncertain to distinguish from zero.

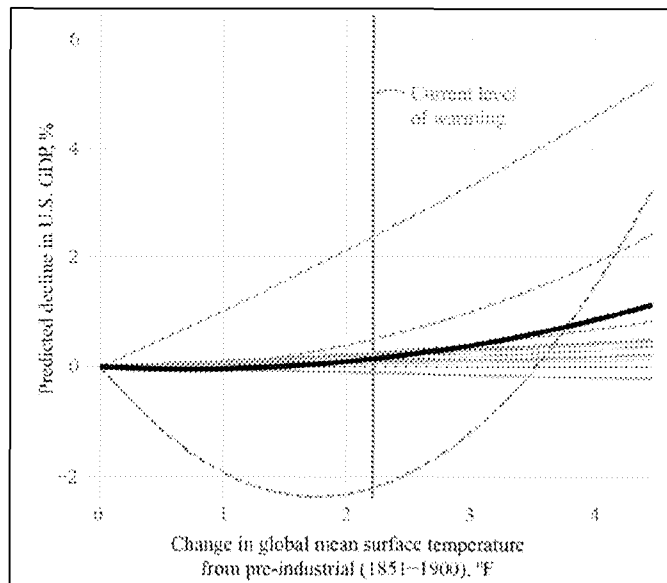
Barker (2023) criticized the DJO12 assumption that countries can be grouped into fixed “poor” and “rich” categories based on their incomes many decades ago. He noted that many countries were once poor but became rich over time, and if this is considered the original temperature effects reported by Dell et al. became small and insignificant.

Berg et al. (2023) argued that countries shouldn’t be grouped into large Rich/Poor categories because they are too heterogeneous. They instead estimated country-specific temperature response coefficients then grouped countries with similar response coefficients into small panels. They separately estimated responses to global and idiosyncratic local temperature shocks to better identify the climate signal in weather data. Overall they found countries experiencing negative effects of warming on growth outnumbered those experiencing positive effects, but only temporarily: eventually the effects reverse such that about twice as many countries experience a net positive growth effect. They also found global (as opposed to local) temperature changes are much more likely to benefit growth in poor countries than rich ones. In a simulation to 2100 even using the extreme RCP8.5 scenario they computed the average global GDP loss would be only 1.9% compared to a scenario with no warming. That is, instead of the economy growing 400% it would grow 398%. The implication of Nordhaus’ analysis is that trying to prevent the warming would lead to far less than 398% growth.

To summarize, economists have long considered climate a relatively unimportant factor in economic growth, a view echoed by the IPCC itself in the Fifth Assessment Report. Mainstream climate economics has recognized that CO<sub>2</sub>-induced warming may have some negative economic effects but they are too small to justify aggressive abatement policy, and trying to “stop” or cap global warming even at levels well above the Paris target would be worse than doing nothing. An influential study in 2012 suggested that global warming would harm growth in poor countries but it has subsequently been found not to be robust. Studies that take full account of modeling uncertainties either find no evidence of a negative effect on global growth from CO<sub>2</sub> emissions or find poor countries as likely to benefit from it as rich countries.

The expectation that significant global warming would have a small impact on the U.S. economy was acknowledged quietly by the Biden Administration, even as the President was proclaiming a climate emergency. The following figure, from a 2023 OMB-CEA [report](#), shows the expected decrement in U.S.

GDP as a function of temperature rise. The colored lines show the results of a dozen peer-reviewed published studies while the solid black line is their average. The figure could be summarized as “a few percent impact for a few degrees of warming”. Given that the economy’s annual growth rate is expected to be 1-2 percent, the impact of a warming globe is indeed negligible.



Need caption

### 13.2. Models of the Social Cost of Carbon

The Social Cost of Carbon (SCC) is a tool for quantifying the economic impact of carbon dioxide emissions, helping policymakers weigh the costs and benefits of climate policies. It estimates the damage caused by emitting one additional ton of CO<sub>2</sub>, expressed in dollars. More formally, the SCC is the discounted present value of the current and future marginal loss of economic welfare due to an additional ton of CO<sub>2</sub> entering the atmosphere. On its own the SCC is not the appropriate price to attach to CO<sub>2</sub> emissions for the purpose of optimal emissions control but it can be converted into an optimal tax rate by scaling it by the Marginal Cost of Public Funds (MCPF). The theory behind this was first derived by Sandmo (1975) and has been reiterated many times since then by other economists working on the topic (e.g. Parry et al. 1999). The MCPF is the cost in terms of lost private economic welfare of raising public revenue by one dollar and always exceeds unity. If a jurisdiction does not use a carbon tax, this formula still indicates the upper bound on the amount emitters should spend on abatement options at the margin along the optimal policy path. Regulations should be imposed only insofar as they do not impose marginal abatement costs in excess of the optimal tax rate.

#### 13.1.2 Estimating the SCC

Although the literature refers to “estimates” of the SCC, it is not estimated in the way other economic statistics are estimated. For instance, data on market transactions including prices and quantities can be used to estimate the current inflation rate or the growth rate of per capita real Gross Domestic Product, and there are well-understood uncertainties associated with these quantities. But there are no market data available to measure many if not most of the marginal damages or benefits believed to be associated with CO<sub>2</sub> emissions, so these need to be imputed using economic models.

For example, an influential component of some SCC calculations is the perceived social cost associated with changed risk of future mortality due to extreme weather. There is no market in which people can directly attach a price to that risk. At best economists can try to infer such values by looking at transactions in related markets such as real estate or insurance, but isolating the component of price changes attributable to atmospheric CO<sub>2</sub> levels is very difficult.

Economists use IAMs to compute the SCC. Two of the best known IAMs are the Climate Framework for Uncertainty, Negotiation and Distribution (“FUND”, Tol 1997) and Nordaus’ DICE. IAMs embed a stylized global climate model with a very simplified representation of the global economy, including a “damage function” or set of functions relating ambient temperature to local economic conditions. The assumptions embedded in the damage function will largely determine the resulting SCC.

One approach to developing a damage function is to begin with estimates of the costs (or benefits) of warming in specific sectors in countries around the world and aggregate up to a global amount. This was the approach used in FUND. An alternative approach is to develop a simple equation that penalizes global income according to a simple quadratic function of the average global temperature. This approach was used in DICE. In the case of the FUND model many hundreds of parameters had to be selected, whereas in DICE only three were needed and were originally chosen to assign a predetermined penalty (1.2%) to global output as of 3°C warming, with a quadratic term implying that damages grow with the square of the global average temperature anomaly. Barrage and Nordhaus (2024) recently changed the parameters to increase the penalty at 3°C to 1.6%, and added a discrete additional 1.0% GDP penalty at 3°C warming to account for “tipping points” (discrete large-scale environmental changes triggered by crossing a warming threshold) and a “judgmental adjustment” of 0.5% for excluded impacts at 3°C warming. Not surprisingly the newer version of DICE generates much higher SCC estimates than before.

The concepts of estimation and uncertainty do not readily apply to SCC calculations. By comparison, the question of whether precipitation has trended up or down along the South Carolina coast for the past hundred years can be addressed by collecting rainfall data, estimating a trend parameter and calculating statistical confidence intervals using methods with well-understood mathematical properties. In this way uncertainty can, in principle, be resolved by collecting more data and applying more accurate methods. But no amount of data collection can change the fact that many components of the SCC are unknown and rely on judgment and opinion based on knowledge of the underlying literature on the physical effects of climate change.

SCC calculations are thus best thought of as “if-then” statements: *if* the following assumptions hold, *then* the SCC is \$X per tonne. The list of ‘if’ statements includes the premise that the world’s climate and economy work according to the representation in the IAM. One way this may fail to hold is in the timing of warming. Every IAM assumes a value of the Equilibrium Climate Sensitivity (ECS), controls the amount of warming that results from CO<sub>2</sub> emissions and can be freely varied for the purpose of generating a distribution of SCC values associated with uncertainties over ECS. But as Roe and Baumann (2013)

pointed out, time-to-equilibrium increases with the square of ECS, so an upward adjustment of the ECS parameter without an appropriate slowing down of the adjustment process can yield distorted present value damage estimates. In particular, the upper tail of warming associated with some commonly-used ECS distributions is physically impossible for even a thousand years into the future (Roe and Baumann 2013) yet in an IAM would be realized within a couple of centuries. Failure to align ECS with time-to-equilibrium will lead to an overestimate of the SCC value.

### 13.2.2 Variations in the SCC

Every level of the IAM calculation includes assumptions, some more influential than others. Key assumptions include the following.

- The discount rate: Climate damages accrue over a long time horizon, and costs a century or two in the future need to be discounted to the present. The higher the discount rate the smaller the present value of future damages and vice versa. The discount rate represents the opportunity cost of spending money today rather than investing it and then having more to spend tomorrow. Some economists have argued for the use of very low discount rates in SCC calculations, resulting in policy recommendations that favor relatively large immediate investments in CO<sub>2</sub> emission reductions. The downside is that other investments could potentially earn a larger rate of return for society.
- Equilibrium Climate Sensitivity: IAMs have customarily employed a value of 3.0°C or 3.1°C following the IPCC's guidance. Empirically-estimated ECS values tend to be lower than this (see Chapter XX). Dayaratna et al. (2017, 2020, 2023) have shown that use of lower empirically-derived ECS values dramatically lower the resulting SCC estimate, even when low discount rates are used.
- Damage function coefficients: IAMs assume CO<sub>2</sub> and warming cause net harms that increase exponentially with temperature. More recently, IAMs have also incorporated effects from assumed potential climate tipping points. The FUND model took limited but explicit account of CO<sub>2</sub> fertilization effects in agriculture. Since the coefficients were selected prior the publication of the current evidence of global greening and the magnitude of benefits to crops from elevated CO<sub>2</sub> (see Chapters 2 and 10) the growth effects are likely understated. The DICE model (and others) did not explicitly include any CO<sub>2</sub> fertilization benefit, except to the extent it was taken into account in the literature consulted when picking the damage function coefficients. The damage function in FUND contains a region in which low warming yields net benefits in many regions, a finding which is supported by econometric models of warming and growth (Berg et al. 2023) and econometric simulations of agricultural changes (McKittrick 2025). The DICE damage function, by construction, rules out net benefits at any warming level.
- Emission scenarios: IAMs generate SCC estimates that increase as the pre-existing concentration of CO<sub>2</sub> increases. Consequently the value of damages later in the century will be higher, depending on the assumed baseline emissions over the coming decades.
- Abatement costs: IAMs represent the cost to the economy of reducing CO<sub>2</sub> emissions. If CO<sub>2</sub> emission reductions are assumed to be inexpensive, then the model will conclude that the optimal policy should aim for deeper emission cuts and vice versa.

It is informative to ascertain whether SCC results are invariant to changes in some assumptions. But when different assumptions result in higher or lower SCC values, the change in the SCC value does not provide *prima facie* evidence about the validity of the assumptions. For example, in 2023 the US Environmental Protection Agency raised its preferred SCC value about 5-fold over the estimates it had issued ten years earlier. This is not because new data had been collected or better mathematical methods had been invented, but because new assumptions had been used, and the validity of those assumptions was a separate question. One was that global agricultural damages were far higher than previously assumed, based on an analysis in Moore et al. (2017). But as discussed in Section XX, McKittrick (2025) showed that Moore et al. (2017) had used a database in which half the CO<sub>2</sub> change observations were missing. When as many of those observations as possible were recovered from underlying sources and the analysis was rerun, the projected crop yield losses disappeared and turned into gains at all warming levels. Hence the portion of the EPA's SCC revision attributable to agricultural yield losses was unwarranted.

### 13.2.3 Evidence for low SCC

Chapter 2 reviewed evidence on climate change and greening, and Chapter 10 looked at climate change and US agriculture. Evidence shows that CO<sub>2</sub> fertilization has a stronger beneficial effect on agriculture than was known at the time that IAMs like DICE and FUND were parameterized. In particular Haverd et al. (2020) found the observed CO<sub>2</sub> fertilization rate has been almost double what had been predicted by crop models. Dayaratna et al. (2023) used the updated empirical ECS distribution estimate of Lewis (2022), which assimilates modern instrumental and paleoclimatic temperature records, and allowed for a 30 percent gain in the CO<sub>2</sub> fertilization benefit in the FUND model, and found that, even at a low discount rate of 2.5 percent, the median SCC as of 2050 is only \$18.67, with a 24 percent probability of the true value being negative. At a five percent discount rate the median SCC value is negative until the mid-2040s and at 2050 was only \$0.37 with a 49 percent probability of being negative. Thus, under reasonable assumptions a mainstream IAM using updated scientific inputs yields evidence consistent with the SCC not being significantly greater than zero.

It should also be noted that the SCC is focused on the social costs of CO<sub>2</sub> emissions from fossil fuel use. It does not measure the private marginal benefits to consumers and society from the availability of fossil fuels. Public willingness to pay for fuels of all types indicates the value to society of reliable, abundant fossil energy. Tol (2017) estimates that the private benefit of carbon is large relative to the social cost. This can be illustrated by noting that the price of a gallon of gas indicates the marginal value to the consumer of the fuel. Suppose we assume a relatively high Social Cost of Carbon of, say, \$75 per tonne. Deflated by a MCPF value of 1.5 that would result in a carbon tax of \$50 per tonne, which equates to about 44 cents per gallon of gas (Lavelle 2019). A pre-tax price of \$3.00 per gallon would imply the marginal social benefit of the fuel is nearly seven times the marginal social cost.

### 13.3. Summary

It is increasingly being argued that the SCC is too variable to be useful for policymakers. Cambridge Econometrics (Thoung 2017) stated it's "time to kill it" due to uncertainties. The UK and EU no longer use SCC for policy appraisal, opting for "target-consistent" carbon pricing (UK Department for Energy Security and Net Zero 2022, Dunne 2017). However the weaknesses of the SCC concept don't mean that other regulatory measures are inherently better or more efficient. Many climate regulations (such as electric vehicle mandates, renewable energy mandates, energy efficiency regulations and bans on certain types of home appliances) end up costing far more per tonne of abatement than a simple price on carbon emissions.

In summary, SCC estimates are highly uncertain due to unknowns in future economic growth, socioeconomic pathways, discount rates, climate damages, and system responses. The SCC is not intrinsically informative as to the economic or societal impacts of climate change. It provides an index connecting large networks of assumptions about the climate and the economy to a dollar value. Some assumptions yield a high SCC and others yield a low or negative SCC. The evidence for or against the underlying assumptions needs to be established independently; the resulting SCC adds no additional information about the validity of those assumptions.

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## 14. U.S. Vehicle-Based CO<sub>2</sub> Emissions and the Global Climate

The EPA's 2009 Endangerment Finding focused on CO<sub>2</sub> emissions from cars and light-duty trucks in the U.S. because Section 202(a) of Clean Air Act mandates the EPA to set emissions standards for motor vehicles if pollutants are found to endanger public health or welfare. Thus, the 2009 Endangerment Finding obligated the EPA to regulate emissions from new motor vehicles.

Two questions that naturally arise are: (1) How large a reduction in CO<sub>2</sub> emissions would result from such regulation? and (2) What would be the climate impact of such regulation?

The first question can be addressed using CO<sub>2</sub> emissions statistics from the EPA and the International Energy Agency (IEA). The second question can be addressed by the fact that the reduction in global warming is proportional to how much global emissions are reduced, keeping in mind that how much the CO<sub>2</sub> content of the atmosphere increases in any given year is the result of total global CO<sub>2</sub> emissions, not just U.S. emissions.

In 2022, the emissions from U.S. cars and light duty trucks totaled 1.03 billion metric tons of carbon dioxide (GtCO<sub>2</sub>). This is only 2.8% of the 36.8 GtCO<sub>2</sub> of global energy-related emissions in 2022. If we were to take into account emissions from land use and cement production, that fraction would be even smaller, but for the purpose of the following calculation, it will suffice.

Even if all CO<sub>2</sub> emissions were eliminated from U.S. cars and light duty trucks in 2022, the impact on global warming would be less than 3%. Would such a tiny impact even be measurable in global temperature data? For the period 1979-2023, which has the most extensive global coverage of a variety of weather data types, warming trends from five global temperature datasets range from +0.163 deg. C per decade from the NCEP/NCAR R1 reanalysis dataset to +0.211 deg. C per decade for the ERA5 reanalysis dataset. The latter estimate is 29% larger than the former, indicating that a 3% reduction in the rate of global warming from eliminating U.S. vehicle CO<sub>2</sub> emissions would be an order of magnitude below the threshold of measurability. Given that global-average temperature is the most robust climate change metric, this means any other climate impacts (e.g. severe weather, floods, drought, etc.) from the elimination of U.S. vehicle CO<sub>2</sub> emissions would be even less significant.

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## 16. Glossary of Terms

**2XCO<sub>2</sub>**: doubling of the atmospheric CO<sub>2</sub> content relative to pre-Industrial times, a commonly used baseline for addressing climate change. In 2025, atmospheric CO<sub>2</sub> concentrations were approximately 50% of the way to 2XCO<sub>2</sub>.

**ABATEMENT**: in the context of pollution, the reduction of harmful impacts through pollution reductions

**ACE (Accumulated Cyclone Energy)**: a statistical measure of a tropical cyclone's energy accumulated over its lifetime, calculated from a summation of the square of maximum sustained wind speeds

**ACIDIFICATION**: a commonly used term for the reduction in ocean pH from more alkaline to less alkaline values

**AEROSOLS**: tiny solid or liquid particles suspended in the air

**ALKALINE**: having a chemical pH greater than 7.0. The "opposite" of acidic, which means a pH less than 7.0

**AMBIENT**: relating to the immediate surroundings of something

**ANTHROPOGENIC**: created by humans

**AR (IPCC Assessment Reports)**: periodic assessments published by the IPCC evaluating current knowledge of the climate system, global change, and associated issues. The most recent was AR6 in 2023.

**BIOMASS**: the total quantity or weight of organic matter in a given area or volume

**CARBON**: popular and widely used shorthand term for carbon dioxide

**CMIP (Coupled Model Intercomparison Project)**: The IPCC's organized effort to compare many different global ocean-atmosphere climate models when they are all forced with the same emissions scenario(s)

**CONUS**: the contiguous 48 U.S. states

**DICE (Dynamic Integrated model of the Climate and Economy)**: An Integrated Assessment Model (IAM) developed by William Nordhaus in 1993.

**DISCOUNT RATE**: here, the rate used to convert future costs and benefits of environmental regulations into their present value. A high discount rate reduces the present value of future environmental benefits from regulating sooner; a low discount rate favors long-term benefits of regulating sooner.

**DRY ICE**: frozen carbon dioxide

**ECONOMETRICS**: the branch of economics concerned with the use of math and statistics in describing economic systems

ECS (Equilibrium Climate Sensitivity): The total amount of eventual global-average surface warming in response to a hypothetical doubling of the atmospheric CO<sub>2</sub> concentration compared to pre-Industrial levels.

EL NIÑO: the warm phase of ENSO, involving weaker upwelling of cold water off the South American coast and weaker Pacific trade winds.

EMISSIONS SCENARIO: An assumed scenario of future greenhouse gas emissions (or resulting atmospheric concentrations) based upon assumptions regarding global economic activity, the prevalence of fossil fuel use, and (sometimes) global carbon cycle model estimates of the rate of CO<sub>2</sub> uptake by land and ocean.

ENDANGERMENT FINDING (EF): the 2009 finding by the Administrator of the EPA that CO<sub>2</sub> emissions endanger human health and welfare

ENSO: El Niño – Southern Oscillation, a prominent natural climate fluctuation involving year-to-year variations in the upwelling of cold water off the equatorial coast of South America and associated strengthening or weakening of trade winds across the Pacific Ocean

FACE: (Free-Air CO<sub>2</sub> Enrichment) large-scale open-air studies that expose plants to elevated CO<sub>2</sub> levels, simulating future climate scenarios.

FOSSIL FUEL: a natural fuel such as coal or natural gas formed in the geological past from the remains of living organisms

FUND: An Integrated Assessment Model (IAM) developed by Richard Tol in 1997.

GBR (Great Barrier Reef): the world's largest coral reef ecosystem located off the northeast coast of Australia

GDP (Gross Domestic Product): total market value of all the final goods and services produced within a country's border, usually over one year

GHCN: the Global Historical Climatology Network, consisting of a time-varying number of globally distributed weather stations making hourly, daily, or monthly measurements of precipitation, temperature and sometimes snowfall and snow depth.

GLOBAL GREENING: the satellite-observed increase in greenness in most vegetated land areas observed since the early 1980s

GNP (Gross National Product): total market value of all the final goods and services produced by the citizens a country, usually over one year

GREENHOUSE EFFECT (GHE): the tendency for any planetary atmosphere containing greenhouse gases to be warmer in the lowest layers than if those gases did not exist.

GREENHOUSE GAS (GHG): an atmospheric gas that absorbs and emits infrared (IR) radiation, especially water vapor, CO<sub>2</sub>, and methane.

HURST PHENOMENON: see long term persistence.

**HYDROLOGY:** the study of the movement of water, especially on land and the atmosphere

**IAM (Integrated Assessment Model):** a computerized tool that combines economics, climate science, and social sciences to provide quantitative relationships between human and Earth systems, helping to inform policy decisions

**IEA:** International Energy Agency

**IPCC (Intergovernmental Panel on Climate Change):** A panel of international experts and governmental representatives established by the United Nations and World Meteorological Organization in 1988 to provide governments at all levels with scientific information that they can use to develop climate policies

**IR (Infrared):** heat radiation that all solid objects and greenhouse gases emit by virtue of their temperature.

**LA NIÑA:** the cool phase of ENSO, involving stronger upwelling of cold water off the South American coast and stronger Pacific trade winds.

**LONG TERM PERSISTENCE (LTP, or HURST PHENOMENON):** the tendency for natural systems such as precipitation, droughts, and floods to have persisting behavior over time, as opposed to random behavior, which impacts our interpretation of long-term trends in climate data

**MAIZE:** corn

**MODEL:** a computer code or collection of codes which quantify our knowledge of various processes and the interactions between those processes

**MORTALITY:** death or number of deaths, usually expressed for a specific population and period

**NCA (National Climate Assessment):** A periodic report mandated by the Global Change Research Act of 1990 summarizing the impact of climate change on the United States> There have been five NCA reports: NCA1 (2000), NCA2 (2009), NCA3 (2014), NCA4 (2017-18), and NCA5 (2023)

**OECD (Organization for Economic Cooperation and Development):** a specific list of 38 countries having a democratic system of government and free economic systems

**PALEOCLIMATE:** climate of the distant past, before modern weather instruments were widely used (typically pre-1850), necessitating the use of “proxy” measurements such as tree rings, ice core, pollen records, etc.

**PDI (Power Dissipation Index):** a statistical estimate of the accumulated destructive potential of a tropical cyclone over time, calculated as a summation of the cube of the maximum sustained wind speeds

**PHOTOSYNTHESIS:** the process by which plants grow, requiring carbon dioxide, water, and light at sufficiently warm temperatures (10 to 35 deg. C for optimal function)

**PPM:** parts per million, a measure of the concentration of a substance in (for example) the atmosphere

**PRE-INDUSTRIAL:** the historical period before which human greenhouse gas emissions were considered significant, usually assumed to be the mid-1700s

**RADIATIVE FEEDBACK:** a change in the balance between absorbed solar radiation and emitted infrared (IR) radiation, referenced to the top of the atmosphere, caused by changes in surface temperature

**RADIATIVE FORCING:** the change in the balance between absorbed solar radiation and emitted infrared (IR) radiation, referenced to the top of the atmosphere, caused by changes in greenhouse gases, anthropogenic aerosols, volcanoes, etc.

**RCP SCENARIOS:** Representative Concentration Pathways, different scenarios for future greenhouse gas emissions and their impact on the atmosphere, introduced in the IPCC's Fifth Assessment Report (AR5). RCP scenarios have a number label (e.g. RCP6.0) indicating how much radiative forcing they assume in 2100 relative to pre-Industrial times, in Watts per sq. meter. RCP4.5 and RCP6.0 are intermediate scenarios, whereas RCP8.5 is an extreme scenario with very large future emissions of greenhouse gases.

**RICARDIAN ANALYSIS:** a method used in environmental economics to estimate the economic impacts of climate change, particularly on agriculture

**SOCIAL COST OF CARBON (SCC):** an estimate of the total economic damages, measured in dollars, caused by emitting one additional ton of CO<sub>2</sub> into the atmosphere

**SSP SCENARIOS:** Shared Socioeconomic Pathways, different scenarios for future greenhouse gas emissions and their impact on the atmosphere, introduced in the IPCC's Sixth Assessment Report (AR6). Some of the SSP scenarios are analogous to the older RCP scenarios, for purposes of continuity and comparison to earlier climate model assessments.

**TC:** tropical cyclone

**TMAX:** the daily maximum surface air temperature

**TMIN:** the daily minimum surface air temperature

**TOA:** top of atmosphere

**TOXICOLOGY:** the study of the adverse effects of chemical substances on living organisms.

**TREND:** usually, the linear regression slope fit to a time series of data, one of the most commonly used metrics to describe climate change over a long period of time

**UHI (Urban Heat Island):** the tendency for inhabited areas to be warmer than their rural surroundings, due to the replacement of natural land and vegetation with roads, parking lots, buildings, and waste heat sources.

**USHCN:** the U.S. Historical Climatology Network, consisting of quality-controlled temperature and precipitation data from 1,218 surface weather stations

## 17. About the authors

John Christy, Ph.D.

Judith Curry, Ph.D.

Steven Koonin, Ph.D.

Ross McKittrick, Ph.D.

Roy Spencer, Ph.D.

---

**From:** Travis Fisher <travis.scott.fisher@gmail.com>  
**Sent:** Wednesday, May 7, 2025 11:38 AM  
**To:** Judith Curry  
**Cc:** Roy Spencer; Steven Koonin; John Christy; Ross McKittrick  
**Subject:** Re: Glossary

I'd be happy to take on the next version of the glossary. You don't need a PhD to do that, and I'm happy to take anything like that off your hands!

On Wed, May 7, 2025 at 10:31 AM Judith Curry <curry.judith@gmail.com> wrote:  
thx for doing this. There are alot of acronyms used in the various chapters that should be included also

On Wed, May 7, 2025 at 3:45 AM Roy Spencer <roywspencer@hotmail.com> wrote:  
Attached is my first cut at a glossary, 64 terms so far based upon my reading of the chapters.

I've omitted obvious things like EPA, CO2, NOAA, NASA...

I'm sure I missed a few terms, and feel free to make edits.

Of course, this could all wait until everything else is completed.

-Roy

---

**From:** Steven Koonin <steven.koonin@gmail.com>  
**Sent:** Tuesday, May 6, 2025 9:02 PM  
**To:** John Christy <climateman60@gmail.com>  
**Cc:** Ross McKittrick <ross.mckittrick@gmail.com>; Judith Curry <curry.judith@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>  
**Subject:** Re: Ch 8 Extreme weather

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John, do decouple for at least a few days. I've made the mistake of not doing so on a few vacations, with great regrets afterward.

Steven Koonin

On May 6, 2025, at 21:53, John Christy <climateman60@gmail.com> wrote:

All

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My preference is for someone to read the thing and write the summary (8.4) based upon what a fresh set of eyes would conclude. Steve? Roy?

Ross. The panel charts of the individual station precipitation take up a lot of real estate and I think the value per acre is low. Since you calculated 3 statistics for each station, could you craft a bar chart or something to show that result? You would then have 9 charts, one for each of the 3 statistics and one each of the three regions. The nine charts may be panelized and fit on one plot. I know for us it's important for people to see the actual data (which is why I had those colored bar charts - now monochromatic), but it may be overkill for this document.

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I especially like the way you parsed the Sidebar and I hope smart people will finally understand that when dealing with climate, our sample is pathetically small from which to draw hard conclusions.

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I reran the Heatwave results to use 6-day periods as did NCA5. NCA5 was slick though. By choosing 1961-90 their background climatology was cold relative to decades before and since, so that results outside of those 30 years would produce a lot of days that exceed the percentile threshold. Then in the urban heatwave website, they started in 1960, assuring a result that more temps would exceed the threshold in post-1990 years.

That's all I've got.

Aloha

John C.

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Director, Earth System Science Center  
Professor, Atmos and Earth Science  
Alabama State Climatologist  
The University of Alabama in Huntsville  
[climateman60@gmail.com](mailto:climateman60@gmail.com)

<8 Extreme weather.JRC.May07.docx>

On May 6, 2025, at 5:25 PM, John Christy <[climateman60@gmail.com](mailto:climateman60@gmail.com)> wrote:

Steve

As Ross notes, the precipitation section is simply an update of our 2019 paper. The daily temperature work from the supplemented USHCN records is in a paper under review (but I suspect will have difficulty being accepted). The data are from the official USHCN site with my supplements adding about 10 percent to cover the missing data. There are about 41 million temperatures here, so I added about 4 million. Thus the results are dominated by publically-available data for others to check. If I get the go-ahead for publication, I can put the complete datafiles on a server for anyone to use.

John C.

John Christy  
Director, Earth System Science Center  
Professor, Atmos and Earth Science  
Alabama State Climatologist  
The University of Alabama in Huntsville  
[climateman60@gmail.com](mailto:climateman60@gmail.com)

On May 6, 2025, at 3:48 PM, Ross McKittrick  
<[ross.mckittrick@gmail.com](mailto:ross.mckittrick@gmail.com)> wrote:

The underlying analysis is all from John's and my Journal of Hydrology paper for which the code is already online. John updated and expanded the data sets and I ran them through the same code.

On Tue, May 6, 2025 at 4:41 PM Steven Koonin  
<[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)> wrote:

A thought about the analysis of long-term CONUS data, which as John knows I like very much:

If some (most?) of this work is as-yet unpublished in a peer-reviewed journal, I'd think you've got to make the expanded and in-filled database (and analysis code?) publicly accessible so that the work can be checked. Are you prepared to do that (at least for the "final", if not the "draft")?

SEK

---

**From:** Ross McKittrick <[ross.mckittrick@gmail.com](mailto:ross.mckittrick@gmail.com)>  
**Sent:** Tuesday, May 6, 2025 1:05 PM  
**To:** John Christy <[climateman60@gmail.com](mailto:climateman60@gmail.com)>  
**Cc:** Judith Curry <[curry.judith@gmail.com](mailto:curry.judith@gmail.com)>; Roy W. Spencer <[roywspencer@hotmail.com](mailto:roywspencer@hotmail.com)>; Travis Fisher <[travis.scott.fisher@gmail.com](mailto:travis.scott.fisher@gmail.com)>; Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)>  
**Subject:** Re: Ch 8 Extreme weather

Here's another edition of Ch 8 on extremes taking Judy's and John's points into account. The IPCC/NCA review is ported to an Appendix. I added a paragraph about LTP to the intro. I've incorporated the NE data. The bulk of the chapter is John's US temperature and precip data analysis with some additional material on wildfires, drought and TCs. For the US temperature extremes I moved the range figure to come just after the hot/cold extremes count because I think they both make a coherent point namely that the US becoming less extreme because heat events are rising more slowly than cold events are warming. There will still need to be an overall chapter summary but I'm going to move on to other chapters now. I'll put this in the Dropbox.

On Tue, May 6, 2025 at 12:12 PM John Christy <[climateman60@gmail.com](mailto:climateman60@gmail.com)> wrote:

All

We can fill in without much trouble the change, or lack thereof, of “high impact” weather events (mainly wind and flooding like hurricanes, tornadoes etc) in the CONUS Extreme chapter. The temp and precip metrics are important because they are just long enough to essentially tell us Mother Nature has a mind of her own.

1. I'll look at Ross's version of 8 soon, but my hope was that Ross would translate the statistical remarks into the correct language(eg are their more precise words that chaotic, episodic, stochastic, etc).

2. We have analyses of the CONUS with more complete datasets than the NCA used (recall NCA analyses depended essentially on a small group at NCEI using datasets that (a) were not very consistent in time, (b) could promote alarm and (c) already easy for them to get to. Our datasets have literally hundreds of thousands of manually keyed-in observations for temporal consistency. In other words, this lets people know we can address these issues from soup to nuts - we're not armchair climate scientists ... we can reproduce what they did, but make the analysis more comprehensive to address the questions.

John C.

Sent from my iPhone

On May 6, 2025, at 4:14 AM, Ross McKittrick

<[ross.mckittrick@gmail.com](mailto:ross.mckittrick@gmail.com)> wrote:

Just read your attribution chapter. I hadn't picked up on the gap between IPCC Ch 11 vs Ch 12 language but i see your point that rather than promoting one set of attribution findings we should explain that even within the same AR different authors assessed things differently. One option is to leave Ch 6 where it is but reverse the order of Ch 7 and 8 while retitling the latter as you suggest. That way, having established the extreme weather types for which there are no detectable trends it will more naturally follow that they won't be discussed in the attribution chapter.

On Tue, May 6, 2025 at 9:45 AM Judith Curry  
<[curry.judith@gmail.com](mailto:curry.judith@gmail.com)> wrote:

Ok, but the summary table (12.12 from AR6) is inconsistent with conclusions in AR6 ch 11 (I point this out in section 6.4 of my attribution chapter).

In my mind, the main point is disagreement and ambiguity I would suggest chapter 8 going before chapter 6, retitling it as US Weather and Climate Extremes, and make it more of a data chapter, not an attribution chapter (I would put table 12.12 in the attribution chapter if you want to include the actual table)

On Tue, May 6, 2025 at 6:39 AM Ross McKittrick <[ross.mckittrick@gmail.com](mailto:ross.mckittrick@gmail.com)> wrote:

I like john's material too which is why I included it and am working on the extended regional analyses. But on this topic people are heavily primed to believe that extreme weather of all kinds is getting worse due to climate change. The assertion shows up everywhere climate change is discussed including in academic papers. I think it is very valuable to show people that neither the IPCC nor the NCA support such this view. We should at least lead off with the summary table. The library of quotes can go to an appendix but I have found in my public speaking that they have considerable persuasive force for most people. We also need to address floods, droughts, hurricane landfalls, tornadoes etc. I don't see any reason to delete all that material.

On Tue, May 6, 2025 at 9:22 AM Judith Curry <[curry.judith@gmail.com](mailto:curry.judith@gmail.com)> wrote:

I actually liked John's chapter. I would have retitled it "US temperature and rainfall extremes"

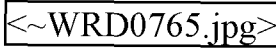
I think this is more relevant than a complete rehash of everything the last 3 IPCC reports have stated for every conceivable severe weather event.

John's version meshes very well with my version of chapter 6. Read especially section 6.4 of my chapter. I note a discrepancy between chapters 11 and 12 in terms of detecting and attributing extreme events. This is the main point in my opinion, there is ambiguity in all this. Lets focus on pointing out the problems/challenges, and topics that are particularly relevant for the US

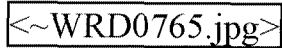
On Mon, May 5, 2025 at 7:47 PM Ross McKittrick <[ross.mckittrick@gmail.com](mailto:ross.mckittrick@gmail.com)> wrote:

I have wrangled the extreme weather chapter into something I hope flows better and is more readable. I adopted Judy's editorial changes and then the new changes I made are in red. I added some new Figures showing results on PC and SE data and will add the NE chart when I get the data. I also made some labeling suggestions including for the 3 rainfall charts that are hard to understand. Section summaries and an overall summary are still needed.

Ross

--  


Judith Curry, President  
CFAN - Climate Forecast Applications Network  
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**Sent:** Wednesday, May 7, 2025 10:32 AM  
**To:** Roy Spencer  
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**Subject:** Re: Glossary

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SEK

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**Sent:** Tuesday, May 6, 2025 1:05 PM

**To:** John Christy <climateman60@gmail.com>  
**Cc:** Judith Curry <curry.judith@gmail.com>; Roy W. Spencer  
<roywspencer@hotmail.com>; Travis Fisher  
<travis.scott.fisher@gmail.com>; Steven Koonin  
<steven.koonin@googlemail.com>  
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Ross

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<~WRD0765.jpg>

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[curry.judith@cfanclimate.com](mailto:curry.judith@cfanclimate.com) | +1.404.803.2012  
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---

**From:** Roy Spencer [roywspencer@hotmail.com]  
**Sent:** 5/7/2025 10:45:50 AM  
**To:** Steven Koonin [steven.koonin@gmail.com]; John Christy [climateman60@gmail.com]  
**CC:** Ross McKittrick [ross.mckittrick@gmail.com]; Judith Curry [curry.judith@gmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]  
**Subject:** Glossary  
**Attachments:** GLOSSARY [RS].docx

Attached is my first cut at a glossary, 64 terms so far based upon my reading of the chapters.

I've omitted obvious things like EPA, CO2, NOAA, NASA...

I'm sure I missed a few terms, and feel free to make edits.

Of course, this could all wait until everything else is completed.

-Roy

---

**From:** Steven Koonin <steven.koonin@gmail.com>  
**Sent:** Tuesday, May 6, 2025 9:02 PM  
**To:** John Christy <climateman60@gmail.com>  
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**Subject:** Re: Ch 8 Extreme weather

I was expecting to read/comment/edit Chapter 8 tomorrow (Wednesday), so I'll use this version. Roy, if you beat me to a summary, that's fine, else I'll take it on.

John, do decouple for at least a few days. I've made the mistake of not doing so on a few vacations, with great regrets afterward.

Steven Koonin

On May 6, 2025, at 21:53, John Christy <climateman60@gmail.com> wrote:

All

Here is a cleaned up version of chapter 8 which you will likely not see until 7 May, so that is the date.

My preference is for someone to read the thing and write the summary (8.4) based upon what a fresh set of eyes would conclude. Steve? Roy?

Ross. The panel charts of the individual station precipitation take up a lot of real estate and I think the value per acre is low. Since you calculated 3 statistics for each station, could you craft a bar chart or something to show that result? You would then have 9 charts, one for each of the 3 statistics and one each of the three regions. The nine charts may be panelized and fit on one plot. I know for us it's important for people to see the actual data (which is why I had those colored bar charts - now monochromatic), but it may be overkill for this document.



As to one of the statistics, I believe 3-day totals will be more meaningful and accurate than 1-day totals. I could send you a file of the heaviest 3-day total for each station and each year and you can do the analysis from there.

I especially like the way you parsed the Sidebar and I hope smart people will finally understand that when dealing with climate, our sample is pathetically small from which to draw hard conclusions.

I also enjoyed the added words on LTP. In fact do you have a few sentences that expand that a little to talk about the erratic nature of precipitation (spatial and temporal) in fancy statistical terms which means finding statistical significance in such a variable is a tough job?

I redid the number-of-event bar charts - all one color now.

I reran the Heatwave results to use 6-day periods as did NCA5. NCA5 was slick though. By choosing 1961-90 their background climatology was cold relative to decades before and since, so that results outside of those 30 years would produce a lot of days that exceed the percentile threshold. Then in the urban heatwave website, they started in 1960, assuring a result that more temps would exceed the threshold in post-1990 years.

That's all I've got.

Aloha

John C.

John Christy  
Director, Earth System Science Center  
Professor, Atmos and Earth Science  
Alabama State Climatologist  
The University of Alabama in Huntsville  
climateman60@gmail.com

<8 Extreme weather.JRC.May07.docx>

On May 6, 2025, at 5:25 PM, John Christy <climateman60@gmail.com> wrote:

Steve

As Ross notes, the precipitation section is simply an update of our 2019 paper. The daily temperature work from the supplemented USHCN records is in a paper under review (but I suspect will have difficulty being accepted). The data are from the official USHCN site with my supplements adding about 10 percent to cover the missing data. There are about 41 million temperatures here, so I added about 4 million. Thus the results are dominated by publically-available data for others to check. If I get the go-ahead for publication, I can put the complete datafiles on a server for anyone to use.

John C.

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Director, Earth System Science Center  
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The University of Alabama in Huntsville  
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On May 6, 2025, at 3:48 PM, Ross McKittrick <ross.mckitrick@gmail.com> wrote:

The underlying analysis is all from John's and my Journal of Hydrology paper for which the code is already online. John updated and expanded the data sets and I ran them through the same code.

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## GLOSSARY

**2XCO<sub>2</sub>:** doubling of the atmospheric CO<sub>2</sub> content relative to pre-Industrial times, a commonly used baseline for addressing climate change. In 2025, atmospheric CO<sub>2</sub> concentrations were approximately 50% of the way to 2XCO<sub>2</sub>.

**ABATEMENT:** in the context of pollution, the reduction of harmful impacts through pollution reductions

**ACE (Accumulated Cyclone Energy):** a statistical measure of a tropical cyclone's energy accumulated over its lifetime, calculated from a summation of the square of maximum sustained wind speeds

**ACIDIFICATION:** a commonly used term for the reduction in ocean pH from more alkaline to less alkaline values

**AEROSOLS:** tiny solid or liquid particles suspended in the air

**ALKALINE:** having a chemical pH greater than 7.0. The "opposite" of acidic, which means a pH less than 7.0

**AMBIENT:** relating to the immediate surroundings of something

**ANTHROPOGENIC:** created by humans

**AR (IPCC Assessment Reports):** periodic assessments published by the IPCC evaluating current knowledge of the climate system, global change, and associated issues. The most recent was AR6 in 2023.

**BIOMASS:** the total quantity or weight of organic matter in a given area or volume

**CARBON:** popular and widely used shorthand term for carbon dioxide

**CMIP (Coupled Model Intercomparison Project):** The IPCC's organized effort to compare many different global ocean-atmosphere climate models when they are all forced with the same emissions scenario(s)

**CONUS:** the contiguous 48 U.S. states

**DICE (Dynamic Integrated model of the Climate and Economy):** An Integrated Assessment Model (IAM) developed by William Nordhaus in 1993.

**DISCOUNT RATE:** here, the rate used to convert future costs and benefits of environmental regulations into their present value. A high discount rate reduces the present value of future environmental benefits from regulating sooner; a low discount rate favors long-term benefits of regulating sooner.

**DRY ICE:** frozen carbon dioxide

**ECONOMETRICS:** the branch of economics concerned with the use of math and statistics in describing economic systems

**ECS (Equilibrium Climate Sensitivity):** The total amount of eventual global-average surface warming in response to a hypothetical doubling of the atmospheric CO<sub>2</sub> concentration compared to pre-Industrial levels.

EL NIÑO: the warm phase of ENSO, involving weaker upwelling of cold water off the South American coast and weaker Pacific trade winds.

EMISSIONS SCENARIO: An assumed scenario of future greenhouse gas emissions (or resulting atmospheric concentrations) based upon assumptions regarding global economic activity, the prevalence of fossil fuel use, and (sometimes) global carbon cycle model estimates of the rate of CO<sub>2</sub> uptake by land and ocean.

ENDANGERMENT FINDING (EF): the 2009 finding by the Administrator of the EPA that CO<sub>2</sub> emissions endanger human health and welfare

ENSO: El Niño – Southern Oscillation, a prominent natural climate fluctuation involving year-to-year variations in the upwelling of cold water off the equatorial coast of South America and associated strengthening or weakening of trade winds across the Pacific Ocean

FACE: (Free-Air CO<sub>2</sub> Enrichment) large-scale open-air studies that expose plants to elevated CO<sub>2</sub> levels, simulating future climate scenarios.

FOSSIL FUEL: a natural fuel such as coal or natural gas formed in the geological past from the remains of living organisms

FUND: An Integrated Assessment Model (IAM) developed by Richard Tol in 1997.

GBR (Great Barrier Reef): the world's largest coral reef ecosystem located off the northeast coast of Australia

GDP (Gross Domestic Product): total market value of all the final goods and services produced within a country's border, usually over one year

GHCN: the Global Historical Climatology Network, consisting of a time-varying number of globally distributed weather stations making hourly, daily, or monthly measurements of precipitation, temperature and sometimes snowfall and snow depth.

GLOBAL GREENING: the satellite-observed increase in greenness in most vegetated land areas observed since the early 1980s

GNP (Gross National Product): total market value of all the final goods and services produced by the citizens a country, usually over one year

GREENHOUSE EFFECT (GHE): the tendency for any planetary atmosphere containing greenhouse gases to be warmer in the lowest layers than if those gases did not exist.

GREENHOUSE GAS (GHG): an atmospheric gas that absorbs and emits infrared (IR) radiation, especially water vapor, CO<sub>2</sub>, and methane.

HURST PHENOMENON: see long term persistence.

HYDROLOGY: the study of the movement of water, especially on land and the atmosphere

IAM (Integrated Assessment Model): a computerized tool that combines economics, climate science, and social sciences to provide quantitative relationships between human and Earth systems, helping to inform policy decisions

IEA: International Energy Agency

IPCC (Intergovernmental Panel on Climate Change): A panel of international experts and governmental representatives established by the United Nations and World Meteorological Organization in 1988 to provide governments at all levels with scientific information that they can use to develop climate policies

IR (Infrared): heat radiation that all solid objects and greenhouse gases emit by virtue of their temperature.

LA NIÑA: the cool phase of ENSO, involving stronger upwelling of cold water off the South American coast and stronger Pacific trade winds.

LONG TERM PERSISTENCE (LTP, or HURST PHENOMENON): the tendency for natural systems such as precipitation, droughts, and floods to have persisting behavior over time, as opposed to random behavior, which impacts our interpretation of long-term trends in climate data

MAIZE: corn

MODEL: a computer code or collection of codes which quantify our knowledge of various processes and the interactions between those processes

MORTALITY: death or number of deaths, usually expressed for a specific population and period

NCA (National Climate Assessment): A periodic report mandated by the Global Change Research Act of 1990 summarizing the impact of climate change on the United States> There have been five NCA reports: NCA1 (2000), NCA2 (2009), NCA3 (2014), NCA4 (2017-18), and NCA5 (2023)

OECD (Organization for Economic Cooperation and Development): a specific list of 38 countries having a democratic system of government and free economic systems

PALEOCLIMATE: climate of the distant past, before modern weather instruments were widely used (typically pre-1850), necessitating the use of “proxy” measurements such as tree rings, ice core, pollen records, etc.

PDI (Power Dissipation Index): a statistical estimate of the accumulated destructive potential of a tropical cyclone over time, calculated as a summation of the cube of the maximum sustained wind speeds

PHOTOSYNTHESIS: the process by which plants grow, requiring carbon dioxide, water, and light at sufficiently warm temperatures (10 to 35 deg. C for optimal function)

PPM: parts per million, a measure of the concentration of a substance in (for example) the atmosphere

PRE-INDUSTRIAL: the historical period before which human greenhouse gas emissions were considered significant, usually assumed to be the mid-1700s

**RADIATIVE FEEDBACK:** a change in the balance between absorbed solar radiation and emitted infrared (IR) radiation, referenced to the top of the atmosphere, caused by changes in surface temperature

**RADIATIVE FORCING:** the change in the balance between absorbed solar radiation and emitted infrared (IR) radiation, referenced to the top of the atmosphere, caused by changes in greenhouse gases, anthropogenic aerosols, volcanoes, etc.

**RCP SCENARIOS:** Representative Concentration Pathways, different scenarios for future greenhouse gas emissions and their impact on the atmosphere, introduced in the IPCC's Fifth Assessment Report (AR5). RCP scenarios have a number label (e.g. RCP6.0) indicating how much radiative forcing they assume in 2100 relative to pre-Industrial times, in Watts per sq. meter. RCP4.5 and RCP6.0 are intermediate scenarios, whereas RCP8.5 is an extreme scenario with very large future emissions of greenhouse gases.

**RICARDIAN ANALYSIS:** a method used in environmental economics to estimate the economic impacts of climate change, particularly on agriculture

**SOCIAL COST OF CARBON (SCC):** an estimate of the total economic damages, measured in dollars, caused by emitting one additional ton of CO<sub>2</sub> into the atmosphere

**SSP SCENARIOS:** Shared Socioeconomic Pathways, different scenarios for future greenhouse gas emissions and their impact on the atmosphere, introduced in the IPCC's Sixth Assessment Report (AR6). Some of the SSP scenarios are analogous to the older RCP scenarios, for purposes of continuity and comparison to earlier climate model assessments.

**TC:** tropical cyclone

**TMAX:** the daily maximum surface air temperature

**TMIN:** the daily minimum surface air temperature

**TOA:** top of atmosphere

**TOXICOLOGY:** the study of the adverse effects of chemical substances on living organisms.

**TREND:** usually, the linear regression slope fit to a time series of data, one of the most commonly used metrics to describe climate change over a long period of time

**UHI (Urban Heat Island):** the tendency for inhabited areas to be warmer than their rural surroundings, due to the replacement of natural land and vegetation with roads, parking lots, buildings, and waste heat sources.

**USHCN:** the U.S. Historical Climatology Network, consisting of quality-controlled temperature and precipitation data from 1,218 surface weather stations





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**From:** Ross McKittrick <ross.mckitrick@gmail.com>  
**Sent:** Friday, May 9, 2025 1:48 PM  
**To:** Judith Curry  
**Cc:** Roy Spencer; Steven Koonin; Travis Fisher; John Christy  
**Subject:** Re: Ch 7 attribution  
**Attachments:** ~WRD0924.jpg; 0.Intro.May9.[RM].docx

I'd like to suggest we aim for a very brief intro. We don't need to say it's a preliminary report or that it will be subject to comment and revision because we are also saying (rightly) that we aren't involved in the EPA process and we don't know what they'll do with it. Secretary Wright has indicated verbally he'd like a larger work product later on, but we don't know what form it will take, and to be honest once he sees it he may decide this report says everything that needs to be said.  
So here's a suggested revision that goes the de minimis route.

On Fri, May 9, 2025 at 9:08 AM Judith Curry <curry.judith@gmail.com> wrote:  
I agree that we can leave this statement out. Our list of references will stand on its own, and we start from the IPCC assessment reports which summarize a large number of papers

On Fri, May 9, 2025 at 2:41 AM Roy Spencer <roywspencer@hotmail.com> wrote:  
Steve's intro is pretty good.

I have a little concern over the following:

*"Nor have we attempted to survey entire literatures related to the topics covered. The scientific and technical material herein only samples vast literature on climate change but is, we believe, more than sufficient to establish our conclusions."*

In my experience, the overwhelming majority of the literature simply assumes climate change is 100% human-caused, dangerous, and demands regulatory action. It doesn't actually demonstrate it.

Or, due to the complexity of the subject the literature deals with minutia that isn't meant to conclude any of that...only to improve our understanding of tiny pieces of the climate change puzzle.

My concern is that someone reading these sentences might conclude, Well, these (few) authors didn't really take the whole body of literature seriously.

Is there a way to rephrase? Or, maybe there's no easy way to address my concern.

-Roy

---

**From:** Steven Koonin <steven.koonin@gmail.com>  
**Sent:** Thursday, May 8, 2025 4:38 PM  
**To:** 'Travis Fisher' <travis.scott.fisher@gmail.com>; 'Roy Spencer' <roywspencer@hotmail.com>  
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<climateman60@gmail.com>

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There is a draft (really just a start) of a joint intro in the 0.Intro.May1 file in the "00.Report Draft" folder (also attached). Y'all should have a look and comment/edit as you see fit.

SEK

---

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## Introduction

This document originated in late March 2025 when Secretary Wright asked the authors to write a report on issues in climate science relevant for energy policymaking, with particular focus on the question of whether carbon dioxide emissions endanger the US public. We agreed to undertake the work on the condition that there would be no editorial oversight by the Secretary, the Department of Energy, or any other government personnel. This condition has been honored throughout the process and the writing team has worked with full independence.

The team writing this report was not involved in, nor briefed on, any Administration plans or processes related to a potential challenge to the 2009 EPA CO<sub>2</sub> Endangerment Finding. We were asked, however, to include some information related to the role of US motor vehicles in global climate change, since that is an issue of relevance to the Department of Energy.

The writing team is grateful to Secretary Wright for the opportunity to prepare this report and for his support for independent scientific inquiry.

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**From:** Judith Curry [curry.judith@gmail.com]  
**Sent:** 5/9/2025 1:08:43 PM  
**To:** Roy Spencer [roywspencer@hotmail.com]  
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I agree that we can leave this statement out. Our list of references will stand on its own, and we start from the IPCC assessment reports which summarize a large number of papers

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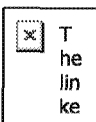
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## Introduction

This document originated in late March 2025 when Secretary Wright assembled an independent team to write a report on issues in climate science relevant for energy policymaking, with particular focus on the question of whether carbon dioxide emissions endanger the US public. The team agreed to undertake the work on the condition that there would be no editorial oversight by the Secretary, the Department of Energy, or any other government personnel. This condition has been honored throughout the process and the writing team has worked with full independence.

The team began working in early April with a deadline of May 28. The short timeline and the technical nature of the material meant that we could not comprehensively review all topics. While the report is intended to be accessible for non-experts, we have omitted some introductory or explanatory material that can easily be accessed elsewhere. Nor have we attempted to survey entire literatures related to the topics covered. The scientific and technical material herein only samples vast literature on climate change but is, we believe, more than sufficient to establish our conclusions.

The team writing this report was not involved in, nor briefed on, any Administration plans or processes related to a potential challenge to the 2009 EPA CO<sub>2</sub> Endangerment Finding. We were asked, however, to include some information related to the role of US motor vehicles in global climate change, since that is an issue of relevance to the Department of Energy.

The writing team is grateful to Secretary Wright for the opportunity to prepare this report and for his support for independent scientific inquiry.

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**Sent:** Thursday, May 8, 2025 5:17 PM  
**To:** Roy Spencer  
**Cc:** Judith Curry; Ross McKittrick; Steven Koonin; John Christy  
**Subject:** Re: Ch 7 attribution

Apologies for the late start -- it's par for the course around here, unfortunately.

As we discussed, I'll coordinate with the Office of Public Affairs (the Sec. Wright team) and the other agencies involved. I'll also work with the Secretary on a draft of his cover letter.

Based on the call, it sounds like the Secretary wants a joint introduction or cover letter from the five of you. I'll defer to you all on whether/how you want to proceed with that, but please let me know if you want any help.

There are two other items I wanted to follow up on:

- 1) My former RA from Cato (Josh Loucks) will join the DOE team this coming Monday, and I'll ask for his help in formatting and finalizing the documents. Would you all flag for me when you think a given chapter is ready to be formatted?
- 2) There is a data visualization wizard on the political team here who can help with any charts or graphs that you want to rework. Please start thinking about which parts of the report you all want to remake or polish instead of borrowing images from other publications. I could go either way on the question of using images or rebuilding graphs -- I just want you to know we've identified someone on the team here who can help with that type of work if we decide to do it.

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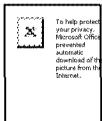
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## 7 Uncertainties in Climate Change Attribution

### 7.1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) distinguishes between detection of climate change and attribution of cause. As defined by the IPCC AR6 WGI Glossary (IPCC, 2025):

*Detection:* “Detection of change is defined as the process of demonstrating that climate or a system affected by climate has changed in some defined statistical sense, without providing a reason for that change. An identified change is detected in observations if its likelihood of occurrence by chance due to internal variability alone is determined to be small, for example, <10%.”

*Attribution:* “Attribution is defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with a formal assessment of confidence.”

Both steps rely on statistical analysis. Detection focuses on whether changes are significant enough to stand out from random variation regardless of cause. Attribution involves comparison of observed events to model-generated counterfactuals. Since experimentation on the climate is not possible attribution requires statistical inference to assess how much human activities, such as GHG emissions, versus natural factors, like volcanic eruptions, explain observed changes. Attribution methods assume all external and internal drivers of the system are known and represented.

There are ongoing scientific debates around attribution methods, especially for attributing extreme weather events to climate change. The IPCC has long cautioned that methods to establish causality in climate science are inherently uncertain and ultimately depend on expert judgement. The Fourth Assessment Report: The Physical Science Basis (Hegerl et al., 2007) explained it as follows:

‘Attribution’ of causes of climate change is the process of establishing the most likely causes for the detected change with some defined level of confidence... unequivocal attribution would require controlled experimentation with the climate system. Since that is not possible, in practice attribution of anthropogenic climate change is understood to mean demonstration that a detected change is ‘consistent with the estimated responses to the given combination of anthropogenic and natural forcing’ and ‘not consistent with alternative, physically plausible explanations of recent climate change that exclude important elements of the given combination of forcings’ (IPCC, 2001)... The approaches used in detection and attribution research described above cannot fully account for all uncertainties, and thus ultimately expert judgement is required to give a calibrated assessment of whether a specific cause is responsible for a given climate change.

The Fifth Assessment Report Working Group II makes the following statement: (Cramer et al., 2014):

“Two broad challenges to the detection and attribution of climate change impacts relate to observations and process understanding. On the observational side, high-quality, long-

term data relating to natural and human systems and the multiple factors affecting them are rare. In addition, the detection and attribution of climate change impacts requires an understanding of the processes by which climate change, in conjunction with other factors, may affect the system in question.”

Because of the complexity of the causal chains in the climate system, investigation of these relationships is exceptionally challenging.

## 7.2 Attribution methods

The Intergovernmental Panel on Climate Change (IPCC) employs several attribution methods to assess the causes of observed climate changes, distinguishing between natural and human-induced factors. Below is a concise description of the key methods that have been used by the IPCC:

*Optimal Fingerprinting* uses linear regression to explain variations in observed climate data as a weighted sum of climate model simulations run with and without anthropogenic forcings. The data used in the regression model are weighted to try to minimize the influence of random noise and the estimation method is chosen to take account of climate model error.

*Time Series Analysis* exploits statistical differences between anthropogenic forcing and natural variability to see which one dominates observed temperatures, and also uses variations in the timing of changes to determine if causal dependence across data series can be inferred.

*Process-Based Attribution* focuses on understanding the physical mechanisms behind observed changes. This approach combines observations, climate models, and theoretical understanding to attribute changes in specific processes to forcings. This approach is often used for regional climate phenomena, such as monsoon changes or polar amplification

*Extreme Event Attribution* assesses in the role of human influence in the likelihood of occurrence or intensity of extreme weather events (e.g. heat waves, droughts). Methods include:

- Probabilistic Event Attribution uses large ensembles of climate model simulations to compare observed events to model-generated counterfactuals
- Storyline Approach examines the physical processes driving an event and evaluates how anthropogenic forcings may have modified those processes

## 7.3 Attribution of global warming

Attribution statements for global warming in the three most recent IPCC Assessment reports are:

AR4: “Most of the observed increase in global average temperatures since the mid-20<sup>th</sup> century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations.” (IPCC, 2007)

AR5: “It is *extremely likely* that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together. The best estimate of the human- induced contribution to warming is similar to the observed warming over this period.” (IPCC, 2013)

AR6: “The *likely* range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019 is 0.8°C to 1.3°C, with a best estimate of 1.07°C. It is *likely* that well-mixed GHGs contributed a warming of 1.0°C to 2.0°C, other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C, natural drivers changed global surface temperature by –0.1°C to +0.1°C, and internal variability changed it by –0.2°C to +0.2°C. It is *very likely* that well-mixed GHGs were the main driver of tropospheric warming since 1979.” (IPCC, 2021)

The AR4 and AR5 attribution statements reference the warming since the mid-20<sup>th</sup> century, the period when greenhouse gas emissions began rapidly increasing. The words “most” and “more than half” are deliberately imprecise, potentially ranging from 51 to 99% of the warming – presumably this imprecision is to account for structural uncertainties such as natural internal variability. The confidence level increases from *very likely* to *extremely likely* from AR4 to AR5. The structure of the attribution statement in the AR6 is fundamentally different, referencing the warming to the period 1850-1900. The AR6 attribution statement is more precise numerically, but with a lower level of confidence at “likely” – the AR6 attributes essentially all of the warming to increases in greenhouse gases. The most confident statement from the AR6 relates to the tropospheric warming since 1979, using the words “main driver” and “*very likely*.”

There are three areas of substantive criticism of the IPCC assessment of the causes of the recent warming: inadequate assessment of natural climate variability, inappropriate statistical methods, and substantial discrepancies between models and observations. The latter is discussed in Chapter 7. The other two factors are discussed herein. Both of these issues are relevant not only in context of the main policy-relevant statement of the IPCC concerning attribution of the recent warming, but also because the global warming attribution provides the basis for extreme event attribution

### **7.3.1 Natural climate variability**

The IPCC AR6 states that natural external drivers since 1850-1900 have changed global surface temperature by –0.1°C to +0.1°C, and internal variability has changed it by –0.2°C to +0.2°C – on average, having essentially no net impact on the warming since 1850-1900. This assessment of the contributions of natural variability has been disputed by a number of publications that question the magnitudes of the contributions from solar forcing and internal variability from the large-scale ocean circulations (R Connolly et al., 2021; W Soon, 2023).

If the Equilibrium Climate Sensitivity to CO<sub>2</sub> is low (Chapter 5), then natural climate variability becomes more important in the attribution of the recent warming. Further, if natural variability is higher, then estimates of the Equilibrium Climate Sensitivity from the historical period would be lower (Scafetta, 2023).

## *Solar variability*

The IPCC AR5 concluded that the best estimate of radiative forcing due to Total Solar Irradiance (TSI) changes for the period 1750–2011 was  $0.05 \text{ W/m}^2$  (Myrhe et al., 2014). The IPCC AR6 acknowledges a much larger range of estimates of changes in TSI over the last several centuries, stating that the TSI between the Maunder Minimum (1645–1715) and the second half of the twentieth century increased by  $0.7\text{--}2.7 \text{ W/m}^2$ , a range that includes both low and high variability TSI data sets (Gulev, 2021). However, the recommended forcing dataset for the CMIP6 climate model simulations used in the AR6 for attribution studies averages two data sets with low solar variability (Matthes, 2017).

While the IPCC AR6 shows a substantially greater solar impact than does the AR5, the overall impact on the climate was assessed to be small compared to anthropogenic forcing of climate change. However, the impact of solar variations on the climate is uncertain and subject to substantial debate – something that you would not infer from the IPCC assessment reports (Lockwood, 2012; Connolly et al., 2021).

Exactly how TSI has changed over time has been a challenging problem to resolve. Since 1978, there have been direct measurements of TSI from satellites. However, the data exhibit non-negligible inconsistencies, and interpreting any multi-decadal trends in TSI requires comparisons of observations from overlapping satellites. There are several rival composite TSI datasets, disagreeing as to whether TSI increased or decreased during the period 1986–96 (the ACRIM gap; see Chapter 4). Further, the satellite record of TSI is used for calibrating proxy models, whereby past solar variations are inferred from sunspots and cosmogenic isotope measurements (Velasco Herrera et al., 2015).

There is substantial evidence for high solar activity in the second half of the 20<sup>th</sup> century (starting in 1959) and extending into the 1990's, before a decline in the early 21<sup>st</sup> century; this period is often termed the “Modern Maximum.” (Chatzistergos et al., 2023; Solanki et al., 2004; Usoskin et al., 2007). However, some scientists have concluded that it is not possible to be confident of any multi-decadal trend in TSI (Schmutz, 2021).

As a result of this uncertainty, some reconstructions for past values of TSI (since 1750) have low variability, implying a very low impact of solar variations on global mean surface temperature, whereas datasets with high TSI variability can explain more than 70% percent of the temperature variability since preindustrial times (Scafetta, 2013; Stefani, 2021). Hence, the choice of which TSI satellite record used in an analysis can substantially influence how much climate change is attributed to human versus natural forcings.

There is growing evidence that other aspects of solar variability, which are referred to as solar indirect effects, amplify TSI forcing or are independent of TSI forcing. Scafetta et al. (2023) suggests that ~80% of solar influence on climate may stem from non-TSI mechanisms. Candidate processes include: solar ultraviolet changes; energetic particle precipitation; atmospheric-electric-field effect on cloud cover; cloud changes produced by solar-modulated galactic cosmic rays; large relative changes in the magnetic field; and the strength of the solar wind. Solar indirect effects are not included in climate models, although indirect methods of estimating these effects suggest



significant influence. However, claims of non-TSI mechanisms influencing climate are uncertain and debated.

### *Natural variability of large-scale ocean circulations*

Variations in global mean surface temperature are linked to recurrent large-scale variations in ocean circulation patterns. These circulation patterns include the Atlantic Multidecadal Oscillation (AMO), the Pacific Decadal Oscillation (PDO) and the El Niño-Southern Oscillation (ENSO). These circulation patterns influence ocean heat uptake and heat distribution, and also influence atmospheric circulation patterns and cloud distributions. There is some debate as to whether these variations are strictly internal to the climate system, or whether this variability can have a solar/astronomical origin or can be influenced by large volcanic eruptions.

While climate models simulate the large-scale ocean circulations and internal climate variability, the simulated magnitude in the multi-decadal band is too low in most models relative to observations, and the phasing of the variability in long-term climate simulations is not synced with the actual, observed climate variations (Kravtsov et al. 2024). Averaging multiple simulations from climate models effectively averages out the internal variations, leaving only the forced climate variability (e.g., CO<sub>2</sub> forcing). With most of the modern warming beginning in the late 1970's, the recent 50-year warming is on the same time scale as the multi-decadal oscillations of the AMO and PDO.

Here are summary statements from the IPCC AR5 and AR6 reports:

“Decadal variability in the Pacific, associated with the PDO or IPO, contributes significantly to regional and global temperature trends, but the relative contributions of internal variability and external forcing are difficult to disentangle in CMIP5 simulations.” (IPCC, 2013)

"Since AR5, there has been increased understanding of the role of internal variability, such as ENSO, PDO, and AMO, in modulating regional climate trends. However, limitations in simulating the exact timing and amplitude of these modes in CMIP6 models contribute to uncertainties in attributing observed changes to anthropogenic forcing (high confidence)." (IPCC, 2021)

The amplitude of the peak-to-trough impact of the multi-decadal oscillations on global temperatures has been assessed by the IPCC AR6: “The likely range of change due to internal variability is -0.2°C to +0.2°C (IPCC, 2021).” This implies a trough-to-peak change of 0.4°C. Over many centuries, any global temperature changes from the troughs and peaks will cancel out, with little to no net impact.

However, with a nominal timescale of 60-80 years for oscillations such as the AMO and PDO, the timing of the peaks and troughs can be confused with the secular trend. This becomes very relevant for attributing the warming for the 50 years since 1975, during which most of the warming has occurred. Even if climate models have the correct amplitude of the multidecadal oscillations, the timing of the peaks and troughs is not adequately simulated, with each model and individual

ensemble simulating a different phasing. Once the simulations of the ensemble members and different models are averaged, the natural internal variability contribution is averaged out, effectively cancelling the role of natural internal variability in the attribution process.

The Great Pacific Climate Shift of 1976-1977 was a notable climatic event characterized by an abrupt change in the North Pacific Ocean's atmosphere-ocean system that interacted with global climate patterns. This shift is closely associated with the Pacific Decadal Oscillation (PDO) that oscillates between warm and cool phases over decades. The 1976 shift marked a transition from a predominantly negative (cool) PDO phase (1947–1976) to a positive (warm) phase (1977 through 2000), with significant implications for global and regional climate patterns including the frequencies of El Nino and La Nina events. The Great Pacific Climate Shift coincided with the beginning of a period of accelerated global warming (REF TO A FIG OF GLOBAL TEMP ANOMALIES ELSEWHERE IN DOC) When the Great Pacific Climate Shift is accounted for in climate attribution analyses since 1950, it has been found that 40 percent or more of the warming in the second half of the 20<sup>th</sup> century was caused by natural internal variability (McLean et al., 2009; Tung and Zhou, 2013; Chylek et al., 2016; Scafetta, 2021).

### ***7.3.2 Optimal fingerprinting***

Optimal fingerprinting is a statistical technique introduced by Allen and Tett (1999) that compares observed climate data to climate model simulations to identify patterns (or "fingerprints") associated with human or natural forcing. It involves taking a vector of observed climate changes, such as warming rates in locations around the world, and decomposing them into a weighted sum of "signals", which are analogues to the observations generated by climate models with different types of forcings. The weights are chosen using a regression method called Total Least Squares. The analysis commonly uses just two signals, one generated by models using only anthropogenic forcings and one using only natural forcings. If the estimated weighting coefficient attached to a signal is significantly different from zero, then that signal is said to be "detected". If it is close to 1.0, then the model generating the signal is said to be consistent with observations. If it is less than 1.0, then the model signal for that forcing is too strong and needs to be scaled down, and vice-versa. Both the observed data and the signals are weighted using a model-generated estimate of patterns of randomness in the climate system so as, in principle, to put maximum weight on regions where natural variability is minimized.

Optimal fingerprinting is the primary tool for attribution in the climate literature. Studies applying it have been cited thousands of times, and it has been prominently featured by the IPCC since the 2001 Third Assessment Report. One of its inherent weaknesses is that results depend on assumptions about the accuracy of climate models, especially regarding their representation of natural variability (IPCC AR5 Ch 10.2.3).

Additionally, a series of papers by McKittrick (McKittrick 2022a, 2022b, 2023, 2025) has challenged the optimal fingerprinting method, arguing that it is inherently unreliable and that commonly used practices in econometrics can provide more valid results. Statistical theory requires that for regression models to yield unbiased coefficients, a set of assumptions called the Gauss-Markov conditions must hold. McKittrick (2022a) argued that the Allen and Tett (1999) methodology violates the Gauss-Markov conditions, leading to potentially biased and inconsistent

fingerprinting coefficients, undermining the reliability of the method. Chen et al. (2023) confirmed this analysis and argued that the method could yield unbiased results but only under very stringent assumptions. McKittrick (2022b) and (2023) raised a further concern that climate scientists—virtually alone among scientific disciplines—have used an estimation method called Total Least Squares (TLS) to estimate anthropogenic greenhouse gas signal coefficients, despite its tendency to be unreliable unless some strong assumptions hold that in practice are unlikely to be true. Under conditions which easily arise in optimal fingerprinting, TLS yields estimates with large positive biases. Thus, any study that has used TLS for optimal fingerprinting without verifying that it is appropriate in the specific data context has likely overstated the result.

McKittrick (2025) presented an empirical example comparing the results of conventional optimal fingerprinting against methods drawn from mainstream econometrics which are known to be valid for the specific application of signal detection. While the IPCC optimal fingerprinting method yields an anthropogenic signal coefficient close to 1.0 on a global temperature data set spanning 1900 to 2010, consistent estimation yields a coefficient around 0.4, which rises to about 0.65 on data spanning 1980 to 2010, implying the model response to greenhouse gases needs to be scaled down by about half to optimally match observations. The natural forcing signal coefficient, by contrast, is between 2.0 and 4.0, implying the climate model signals of natural forcing need to be scaled up two-to four-fold to match observed climate change. The fingerprinting coefficients estimated in McKittrick (2025), when used to scale the average sensitivity of the climate models used to generate the forcing signals in his data set, imply a Transient Climate Sensitivity of 1.4°C, which matches the estimate by Lewis (2022) using a different estimation method and multiple independent data sets.

While these analyses do not prove that all of the results from using the IPCC optimal fingerprinting method are wrong, it does show that the basis on which they were believed to be correct is non-existent – hence reducing confidence in the results.

### ***7.3.3 Time series methods***

The IPCC (AR5 WGI 10.2.2) drew attention to alternative approaches of assessing causality that emerged from the time series econometrics literature. They have the advantage of not depending on assumptions about the accuracy of climate models, but their disadvantage is they depend on assumptions about the data generating process underlying climate and forcing data that are not straightforward to test. The methods, now referred to as climate econometrics, use the tools of unit root testing, Granger causality and cointegration analysis, all of which are familiar in economics and finance and which are slowly being adopted in climate science. Time series analysis methods hold out the possibility of determining whether anthropogenic or natural forcings are the primary drivers of climate change without requiring the use of climate models, although key questions remain unsettled (e.g. Dergiades et al. 2016, Balcombe et al. 2019, Dagsvik et al. 2020, Razzak 2022, Dagsvik and Moen 2023).

Granger causality modeling is a tool for determining directions of influence in data series that move together. “Granger causality” is a statistical, not a physical, concept. If knowing the current value of one variable significantly improves the forecast accuracy of another variable we can infer a causal connection exists; this is called Granger causality. The modeling tools, called vector autoregression, measure direct impulse-response patterns and feedbacks. An application to

the well-known Vostok ice core data revealed an error by Al Gore in his documentary *An Inconvenient Truth*. Gore showed the data and drew attention to the coherence of temperature and CO<sub>2</sub> changes over a 440,000 year span, which he asserted was due to CO<sub>2</sub> driving temperature changes. But temperature changes can also affect atmospheric CO<sub>2</sub> levels. Davidson et al. (2015) examined the series and found that temperature Granger causes CO<sub>2</sub> but not the reverse. In other words on the time scales represented in the Vostok data the coherence in the series is primarily due to the influence of temperature on CO<sub>2</sub> levels not the feedback going from CO<sub>2</sub> to temperature.

In summary, the main statistical methods for attributing causation in climate data are optimal fingerprinting and time series analysis. Applications of the Allen and Tett (1999) optimal fingerprinting method dominate the attribution literature and have underpinned past IPCC conclusions, but results depend on the accuracy of climate models and the method has recently been criticized as inherently biased. Time series methods do not depend on climate models but require assumptions of their own and have generated results that have thus far not converged on a consensus.

#### **7.4 Extreme event attribution (EEA)**

The IPCC AR6 provides an ambiguous assessment of the role of global warming in the historical record of extreme weather and climate events. Chapter 11 of WG1 states (Seneviratne et al., 2021):

“Evidence of observed changes in extremes and their attribution to human influence (including greenhouse gas and aerosol emissions and land-use changes) has strengthened since AR5, in particular for extreme precipitation, droughts, tropical cyclones and compound extremes (including dry/hot events and fire weather). Some recent hot extreme events would have been extremely unlikely to occur without human influence on the climate system.”

By contrast, Chapter 12 of WG1 (Table 12.12) paints a different picture – presumably, the expert judgment of different groups of authors for the two chapters came to different conclusions (Ranasinghe, 2021):

- High confidence in an increase in extreme heat events in tropical regions where observations allow trend estimation and in most regions in the mid-latitudes, medium confidence elsewhere
- Medium confidence in a decrease in extreme cold events in Australia, Africa and most of northern South America where observations allow trend estimation
- No evidence of emergence in the historical period of a change in river floods, heavy precipitation, drought, fire weather, severe wind storms, and tropical cyclones

While the overall issue of detecting changes in extreme weather events and their attribution remains ambiguous, most of the activity in this area relates to the attribution of single extreme weather events. The most prominent effort is the World Weather Attribution (WWA; [worldweatherattribution.org](http://worldweatherattribution.org)), which is an international research initiative that focuses on extreme event attribution analyzing how climate change influences the likelihood and intensity of extreme weather events. The approach used by the WWA runs large ensembles of regional climate models

to compare the event in today's climate, versus a pre-industrial counterfactual climate without human-caused warming.

WWA plays a prominent role in linking extreme weather to climate change and its press releases attract considerable public and policy discussions. However, the WWA's tendency to promote non-peer-reviewed findings, funding ties, open admission that they shape their analyses to serve purposes of litigation and other methodological challenges have sparked controversies, with critics questioning the robustness and impartiality of its conclusions (Pielke Jr. 2024). Despite these issues, WWA's work continues to shape climate science and media narratives. Technical criticisms of the approach include: neglect of a formal detection process; an implicit assumption that 100% of the post-industrial warming is caused by CO<sub>2</sub>; and failure to adequately account for natural internal climate variability.

Because EEA is relatively new many basic methodological issues have yet to be settled in the expert literature. An important challenge is the lack of data. Extreme events are by definition rare. Many analyses of extreme event types (including the US National Assessment Reports) only evaluate data since 1950 or 1970. However, as emphasized by Chapter 8, many of the worst extreme weather and climate events in U.S. history occurred prior to the first half of the 20<sup>th</sup> century including in the early 19<sup>th</sup> century. And if paleoclimate reconstructions are considered, it becomes very difficult for an event to pass the detection thresholds of exceeding what is expected from natural variability, particularly if a reasonably sized geographic region is considered.

Another challenge is defining the event under study. There is a longstanding literature in statistics and econometrics on the challenge of analyzing data with outliers. The issue arises because a data series establishes a probability distribution defining the expected range of observations. If an outlier is observed it might indicate that the underlying process giving rise to the data distribution has changed (which in the weather context would mean a climatic change has been detected) or that the underlying process has multiple regimes each with a different probability distribution, in which case observing an outlier simply means we were temporarily in a different regime, but the system itself was unchanged. If a time series contains only a single outlier event at the end of the series it is not possible to determine which model is the correct one (Chen and Liu 1993). For instance, there might be an "ordinary" weather regime that yields a distribution of summer daytime highs in a particular coastal region, and a second "heatwave" regime that kicks in when an inland blocking event occurs, which yields a temperature distribution centered 15°C higher than the first one. A day with temperatures 13°C above normal would either be an extreme heat anomaly under the first regime or a somewhat cool event under the second, and we have no way in this case of knowing on statistical grounds which view is correct.

Visser and Petersen (2012) and Sardeshmukh et al. (2015) both point out that different distributions may fit observed data equally well but yield very different implications about the likelihood of a specific weather event. Visser and Petersen argue that, in view of the deep uncertainties of extreme weather analysis drawing a connection between individual events and global climate change should be avoided. Furthermore the existence of an outlier at the end of a data series poses the problem that estimates of the event probabilities will be biased whether the outlier is included or excluded (Barlow et al. 2020). Methods to eliminate the bias have not yet been established, leading some experts (e.g. Miralles and Davison 2023) to argue that in settings in which a data series

contains a single extreme event at the end, estimation of a return period for the extreme event will be so biased and uncertain it should be avoided altogether.

In spite of these concerns, the U.S. is presently considering something like the WWA, which is being investigated by a NASEM Panel on Attribution of Extreme Weather and Climate Events and their impacts (NASEM, 2025).

A case studies from a recent high impact extreme events in the U.S. is provided to illustrate the challenges and ambiguities in attributing the frequency and intensity of extreme weather events to human-caused warming.

#### ***7.4.1 Case study – 2021 Western North America heat wave***

The 2021 Western North America heat wave was an extreme heat wave that affected much of Western North America in late June 2021. In particular, surface temperature records were set in Portland, OR (116°F; previous record 107°F) and Seattle, WA (108 °F; previous record 103°F) (Mass et al., 2024).

The WWA team garnered international headlines for their analysis and provided the following attribution statements (WWA, 2021; Philip et al., 2022):

- Based on observations and modeling, the occurrence of this heatwave was virtually impossible without human-caused climate change.
- The event is estimated to be about a 1 in 1000-year event in today's climate.
- The event would have been at least 150 times rarer without human-induced climate change.
- This heatwave was about 2°C hotter than it would have been if it had occurred at the beginning of the industrial revolution (when global mean temperatures were 1.2°C cooler than today).

But an important caveat to the first claim is that other researchers concluded, based on historical weather data, that while a heat wave of the magnitude observed was indeed virtually impossible without anthropogenic climate change, it was also virtually impossible *with* climate change. Bercos-Hickey (2022) noted “these temperatures were virtually impossible under any previously experienced meteorological conditions, with or without global warming.” McKinnon and Simpson (2022) stated “the most likely explanation remains that the weather event itself was ‘bad luck.’” The 2023 Oregon Climate Assessment (Fleischman 2023) concluded that the heat dome would have formed even without climate change and “There is no evidence that the highly unusual combination of weather features that drove the heat dome were made more likely by climate change, and climate models do not project an increase in the frequency of high-pressure ridges over the Pacific Northwest” (Fleischman 2023 p. 49).

Mass et al. (2024) summarizes the proximate sequence of compound events leading to the heat wave. There was a record-breaking midtropospheric ridge over the Pacific Northwest, forced by a tropical disturbance in the western Pacific. This produced record-breaking midtropospheric temperatures, strong subsidence in the lower atmosphere, low-level easterly flow that produced downslope warming on regional terrain and the removal of cooler marine air, and an approaching

low-level trough that enhanced downslope flow. The event occurred at a time of maximum solar insolation, and drier-than-normal soil moisture. Using a storyline approach, Mass et al. assessed that there is no trend in drought and dry soils in the Pacific Northwest; there is no evidence of global warming producing stronger ridges of high pressure, and no observed trend in heat waves or record temperatures in the region. They concluded that although anthropogenic warming may have contributed as much as 2°F to the magnitude of the event, there is little evidence of further amplification of the event from increasing greenhouse gases.

A statistical analysis of a model-based attribution study of this heat wave was conducted by Bercos-Hickey et al. (2022). Because this event is a far outlier and far above the bounds of Generalized Extreme Value distributions fitted from historical data, they concluded that estimates of return times, quantitative changes in event magnitude and frequency, and probability of the extreme temperatures such as provided by the WWA are not accurate and should be interpreted as having low confidence. They found that hindcast attribution methods using an ensemble of regional climate models, combined with Pearl (2009) causal inferences, can provide limited and conditional information about the magnitude of the human influence on this heatwave – they provided a more highly constrained estimate that human activities caused a ~1.4°C–1.8°F increase in the daily maximum temperatures.

Zeder et al. (2023) also concluded that the methods employed by Philip et al. (2022) tend to overstate the rarity of extreme heat waves, leading to a biased perception of the effect of climate change on the heatwave event: “The tendency to overestimate the return period of observed extreme heatwave events may fuel the impression that seemingly impossible heatwave extremes are currently clustering at an unprecedented rate.”

The 2021 Western North America heatwave was a rare and unprecedented compound weather event, that broke century-old temperature records by as much as 9°F. While the WWA team received worldwide publicity for their rapid attribution claims blaming anthropogenic climate change, subsequent peer-reviewed analysis showed that the rare event was not made more probable by global warming.

## **7.5 Summary**

There is an ongoing scientific debate around attribution methods, particularly in attributing extreme weather events to climate change. The IPCC has long cautioned that methods to establish causality in climate science are inherently uncertain and ultimately depend on expert judgement.

There are two areas of substantive criticism of the IPCC assessment of the causes of the recent warming: inadequate assessment of natural climate variability, and inappropriate statistical methods.

Detection of extreme weather events is challenged by their rarity, requiring a long data set and a choice of region and spatial scale to evaluate their occurrence against the background of natural weather and climate variability.

The most robust attribution statements for an extreme event relate to an incremental change (e.g. a temperature change in degrees or percent change in rainfall). Statements related to return times, quantitative changes in event magnitude and frequency, and probability of the extremes are not accurate owing to an inadequate amount of data, and are made with low confidence. There is no evidence in a change of weather or climate regime patterns from increasing greenhouse gases that would amplify or dampen extreme weather events, beyond basic thermodynamic considerations.



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**From:** Judith Curry <curry.judith@gmail.com>  
**Sent:** Friday, May 9, 2025 3:35 PM  
**To:** Roy Spencer  
**Cc:** Ross McKittrick; John Christy; Steve Koonin; Travis Fisher  
**Subject:** Re: 5 Climate Sensitivity

My main objection to the previous text and figure is including old papers. I'm ok with citing several (in addition to Lewis) published since AR6 (2020+), with good data and/or methods

On Fri, May 9, 2025 at 12:23 PM Roy Spencer <roywspencer@hotmail.com> wrote:

If there are 15 studies, they are not created equally.

Estimating ECS from observational datasets has a significant signal-to-noise problem. So, we used the last 50 years when forcing, OHC and Tsfc response are the greatest compared to noise.

Again I will say, if we treat all studies the same, we lose the war because the other side will always have more publications than us.

If you haven't perused our paper, I recommend you do. Then decide on whether it's just one of 15.

-Roy

Sent from my Verizon, Samsung Galaxy smartphone

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From: Ross McKittrick <ross.mckittrick@gmail.com>

Date: 5/9/25 2:10 PM (GMT-06:00)

To: Roy Spencer <roywspencer@hotmail.com>

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On Fri, May 9, 2025 at 3:01 PM Roy Spencer <roywspencer@hotmail.com> wrote:

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Judith Curry, President  
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[curry.judith@cfanclimate.com](mailto:curry.judith@cfanclimate.com) | +1.404.803.2012  
<http://www.cfanclimate.net>



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**From:** Roy Spencer <roywspencer@hotmail.com>  
**Sent:** Friday, May 9, 2025 3:24 PM  
**To:** Ross McKittrick  
**Cc:** John Christy; Judith Curry; Steve Koonin; Travis Fisher  
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**From:** Ross McKittrick <ross.mckitrick@gmail.com>  
**Sent:** Thursday, May 8, 2025 7:50 PM  
**To:** Judith Curry  
**Subject:** Re: Ch 5 merged

In an earlier draft there were formatted superscripts and numbered references. I changed the superscripts to the text as shown so the location of the references didn't get lost during editing.

On Thu, May 8, 2025 at 5:55 PM Judith Curry <curry.judith@gmail.com> wrote:

I'm fine with nearly all of it, except for para on climate models. Any idea what happened to the references (they have been changed by someone to be Source 37, etc. If you know where these references are, i can send them, thx. Then i can have my person do the formatting, citations and refs

On Thu, May 8, 2025 at 1:32 PM Ross McKittrick <ross.mckitrick@gmail.com> wrote:

Took your suggestions and removed the chart.



Judith Curry, President  
CFAN - Climate Forecast Applications Network  
Reno, NV USA  
[curry.judith@cfanclimate.com](mailto:curry.judith@cfanclimate.com) | +1.404.803.2012  
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**From:** Judith Curry [curry.judith@gmail.com]  
**Sent:** 5/8/2025 9:56:26 PM  
**To:** Ross McKittrick [ross.mckittrick@gmail.com]  
**Subject:** Re: Ch 5 merged  
**Attachments:** 5 Climate SensitivityMay8.docx

oops my markup on ch 5

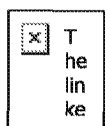
On Thu, May 8, 2025 at 2:55 PM Judith Curry <[curry.judith@gmail.com](mailto:curry.judith@gmail.com)> wrote:

I'm fine with nearly all of it, except for para on climate models. Any idea what happened to the references (they have been changed by someone to be Source 37, etc. If you know where these references are, i can send them, thx. Then i can have my person do the formatting, citations and refs

On Thu, May 8, 2025 at 1:32 PM Ross McKittrick <[ross.mckittrick@gmail.com](mailto:ross.mckittrick@gmail.com)> wrote:

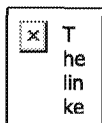
Took your suggestions and removed the chart.

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## 5 Climate Sensitivity to CO<sub>2</sub> Forcing

### 5.1 Introduction

The magnitude of the sensitivity of Earth's climate to increasing concentrations of CO<sub>2</sub> is at the heart of the scientific debate on anthropogenic climate change, and also the public debate on the appropriate policy response to increasing CO<sub>2</sub> in the atmosphere. Equilibrium Climate Sensitivity (ECS) refers to the expected amount of warming averaged over the Earth's surface in response to a doubling of CO<sub>2</sub>, after all climate systems have had time to adjust. Some systems, like temperatures in the troposphere, adjust very rapidly, whereas others such as the deep ocean and ice sheets may take decades or even centuries. A related metric which is helpful for analysis on shorter time scales is the Transient Climate Response (TCR), defined as the amount of warming after 70 years in which atmospheric CO<sub>2</sub> increases by one percent annually.

In 1979 the Charney (1979) Report for the US National Academy of Sciences proposed that the most likely value for ECS was 3.0°C plus or minus 1.5°C. The ECS range between 1.5 and 4.5°C is characterized by the IPCC AR5 as the *likely* range (66 percent probability); the AR5 stated that ECS is *extremely unlikely* (95 percent probability) to be below 1.0°C and very unlikely (90 percent probability) to exceed 6.5°C. This range of ECS values has remained stubbornly wide, despite many individual studies claiming to narrow it. Most recently, the IPCC AR6 narrowed its assessment of the *likely* range of ECS to 2.5–4.0°C and the *very likely* range to be between 2.0 and 5.0°C. This narrowing of the range on the low end is disputed, as will be discussed below.

Uncertainties about ECS are highly consequential for policy making. As will be discussed in Chapter 13, economic models take the ECS value from climate science and use it to project the costs of CO<sub>2</sub> emissions. The traditional ECS value (3.0 °C) has typically yielded modest global social costs of CO<sub>2</sub> emissions, enough to justify some policy actions though mostly deferred to later in the century. If ECS is very high (4.5°C or above) aggressive immediate emission controls become more imperative, whereas values closer to 2.0°C have been shown to imply that no CO<sub>2</sub> emission controls are economically justifiable (Dayaratna et al. 2016, 2020). Obtaining a precise estimate is impossible, so policy making needs to account for the uncertainty.

### 5.2 Model-based methods of computing climate sensitivity to GHGs

The ECS range for the IPCC AR4 and AR5 has been obtained primarily by examining the behaviour of climate models. However, key components of climate models include adjustable parameters and parameterization of small-scale processes such as clouds; hence the models are not dispositive of the actual climate's sensitivity. There are approximately three dozen computer climate models operated by research groups around the world (Cannon 2024). GCMs are valuable tools for understanding the climate system from a theoretical perspective. But the models have become so complex, often with 1 million or more lines of computer code (Brown-Steiner 2024), that it would be prohibitively expensive and time consuming for anyone to replicate the models' projections of climate change, let alone test the myriad model approximations embedded in the computer codes; a climate model typically takes hundreds of experts many years to develop (McSweeney and Hausfather 2018). As a result, these models are published in the scientific literature with little to no independent evaluation (Pirtle et al 2010). Climate modeling thus stands as an unusual class of scientific endeavor wherein researchers validating the scientific claims of others — a hallmark of science (National Academy of Science 2019) — becomes impractical, if not impossible. LACK OF FORMAL VERIFICATION AND VALIDATION IS NOT THE BIGGEST PROBLEM I DON'T THINK THIS CHAPTER IS THE PLACE TO GO

THROUGH ALL THE PHILOSOPHICAL ISSUES WITH CLIMATE MODELS, I WROTE A WHOLE CHAPTER ON THIS IN MY BOOK

I prefer this text if you think we need to address this topic here, but we don't need this here. THE AR6 decided that climate models are useless for determining ECS, and we can just agree with them

Confidence in a forecast model's outputs depends critically on evaluation of the forecasts against real-world observations, both using historical data (hindcasts) and actual forecasts. For model confirmation against observations, there is no straightforward definition of model performance. A critical issue in such comparisons is having reliable global observational datasets with well-characterized error statistics, which represents a separate challenge in itself<sup>1</sup>

Attempts to assess climate model similarity to the observed climate are fraught with challenges: inadequacy of data in terms of coverage and quality; selection of variables to confirm and on which time and space scales; a vast and multi-dimensional parameter space to be explored; model initialization and internal variability; and concerns about circularity with regards to data used in both model tuning and confirmation. Owing to the long timescales present, particularly in the ocean component, there is no possibility of a true cycle of model forecast confirmation and improvement, particularly since the life cycle of an individual model version (order of a few years) is substantially less than the simulation period (order of centuries). Philosopher Wendy Parker argues that known climate model error is too pervasive to allow climate model confirmation to be of use.<sup>11</sup>

In large-scale General Circulation Models (GCMs, aka climate models) ECS is not imposed as a direct parameter; rather, it emerges from the behaviour of the underlying components of the model. Collections of parameterizations are often chosen to produce an expected value of climate sensitivity, particularly with regards to sub-grid-scale cloud processes. Otherwise plausible models and parameter selections have been discarded because of perceived conflict with this warming rate, or aversion to a model's climate sensitivity being outside an accepted range. For example, Mauritsen and Roeckner (2020) state the following regarding their Max Planck Institute climate model:

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ECS can be determined from climate model simulations by doubling the concentration of CO<sub>2</sub>, allowing several centuries for the warming to equilibrate. To avoid the necessity of long simulations, “effective climate sensitivity” is commonly evaluated from a 150-year simulation in response to a sudden quadrupling of CO<sub>2</sub>. The spread of ECS values from the CMIP5 climate models (used in the AR5) was 2.0–4.7°C; the spread has increased for the CMIP6 models (used in the AR6) to between 1.8 and 5.7°C [sources 37,38]. Far from the science being settled in relation to the response of the climate system to increasing greenhouse gas concentrations, insofar as it is represented by climate models, uncertainties appear to be growing. The main cause of the overall upward shift in ECS in CMIP6 relative to CMIP5 is a larger positive cloud feedback, driven by changes to the cloud parameterizations in many CMIP6 models.[source 39]

Because of concerns about model tuning and the high sensitivity to cloud parameterizations, the IPCC AR6 (2021) did not rely on climate model simulations in their assessment of climate sensitivity, relying on other methods in its assessment instead, chiefly a recent empirical estimate.

### **5.3 Data-driven methods of computing climate sensitivity to GHGs**

Climate sensitivity can also be estimated from instrumental records of surface temperatures and ocean heat content, combined with estimates of how climate forcings (e.g., greenhouse gases, solar, volcanoes, aerosols) have changed in the past.[source 40] Using this information, a simple empirical model called an Energy Balance Model can be estimated. It requires estimating a feedback parameter whose uncertainties are highly amplified in the resulting ECS (Roe and Baker, 2007).

The accuracy of the data-driven methods depends on the quality of the input data. Assumptions are needed about ocean heat storage, and the ocean data is inadequate. The greatest source of uncertainty is the amount and composition of aerosol particles and their interactions with cloud radiative properties (the so-called aerosol indirect effect). Climate models exhibit warming in response to GHGs but cooling in response to aerosols (Schwartz et al. 2007). Observed 20<sup>th</sup> century warming can be shown to be consistent either with low ECS and low aerosol cooling or high ECS and high aerosol cooling. Since fossil fuel use adds both GHGs and aerosols to the atmosphere, both effects need to be estimated to isolate the warming effect of CO<sub>2</sub>. Over time, the IPCC’s estimate of the cooling effect of aerosols has declined (Lewis 2022).



Paleoclimate proxies are also used to evaluate the sensitivity of past climates, by comparing paleoclimate changes in the Earth's temperatures to estimates of changes in forcings. The two most informative periods are the last glacial maximum (around 20,000 years ago), which was about 3–7°C colder than today, and a mid-Pliocene period (roughly three million years ago), which was 1–3°C warmer than today.[source 41] The limits on cooling during the last glacial maximum give the best single evidence that high values of climate sensitivity are unlikely. However, paleoclimate estimates are associated with very large uncertainties in the estimated temperatures and forcings. Further, estimates of climate sensitivity based on past climate states may not be representative of the current state of the climate system.

A recurring theme in the climate literature is that ECS estimates based on historical data are smaller than ECS estimates inferred from climate models (Sherwood and Forest 2024). About 15 estimates appeared in the peer-reviewed literature between 2012 and 2024 yielding ECS best estimates between 1.0°C and 2.5°C, although critics have questioned some of the methods and the data quality. For the AR6, the IPCC placed primary weight on the results of Sherwood et al. (2020) that combined historical and paleoclimate proxies and yielded a best estimate of 3.1°C. Lewis (2022) raised a number of concerns about this result, including methodological errors, outdated input values, and use of subjective versus objective Bayesian priors in the analysis. Lewis' analysis found that climate sensitivity is estimated to be much lower and better constrained than in the Sherwood et al. analysis – median 2.2°C (1.8–2.7°C in the 17–83 percent *likely* range, and 1.6–3.2°C in the 5–95 percent *very likely* range). Lewis' analysis implies that climate sensitivity is considerably more likely to be below 2°C than above 2.5°C. The IPCC AR6 estimated only a 5 percent probability that ECS was below 2.3°C, whereas Lewis estimated it to be over 50 percent. The most recent publications on the debate between Sherwood et al. and Lewis further defend their respective positions: Sherwood and Foster (2024) and Lewis (2025).

A recent argument, which the IPCC AR6 emphasized, is that data-driven ECS estimates might understate the future warming response to GHGs based on a so-called “pattern effect” (Forster et al 2021). The tropical Pacific is believed to be highly influential on the overall efficiency with which the Earth's climate radiates heat to space, but in some regions heat is more efficiently removed from the climate system than from others. If in a warming climate there is a weakening of the west-to-east temperature gradient in the tropical Pacific, the result would be a concentration of warming in a region where heat is less efficiently removed, raising the ECS of the Earth's climate system. Most climate models simulate that rising GHGs will weaken the east-west temperature gradient, which led the IPCC in the AR6 to conclude that data-driven ECS estimates understated the *future* ECS value.

However, Seager et al. (2019) pointed out that, contrary to models, the east-west temperature gradient has been strengthening rather than weakening over time. They further argued that the mechanism predicting otherwise in climate models was based on a faulty characterization of oceanic dynamics and there is no reason to expect the gradient to weaken. A similar argument was recently made by Lee et al. (2024), who concluded that “the trajectory of the observed trend reflects the response to increasing GHG loading in the atmosphere”; in other words, GHG warming should lead to a future strengthening rather than a weakening of the temperature gradient. Increased efficiency of atmospheric cooling implies, if anything, that the future ECS in a warming climate may be *lower* than current estimates.

## 5.5 Transient Climate Response

The Transient Climate Response (TCR) is of greater utility in providing an observational constraint on climate sensitivity. TCR is the amount of warming that would occur at the time when CO<sub>2</sub> doubles,

having increased gradually by 1 percent each year over a period of 70 years. Relative to the ECS, observationally-determined values of TCR avoid the problems of uncertainties in ocean heat uptake and the fuzzy boundary in defining equilibrium arising from a range of timescales for the longer-term feedback processes (e.g., ice sheets). TCR is more generally related to peak warming and better constrained by historical warming, than ECS. The IPCC AR6 judged the *very likely* range of TCR to be 1.2–2.4°C. **[source 47]** In contrast to ECS, the upper bound of the TCR is more tightly constrained. For comparison, the TCR values determined by Lewis (2023) is 1.25 to 2.0°C, showing much better agreement with the AR6 values than was seen in a comparison of the ECS values.

A related but more flexible parameter is the Transient Response to cumulative carbon Emissions, or TCRE, which relates global temperature change to the cumulative emissions. TCRE is based upon a linear relationship between global average temperature and cumulative emissions, which holds for cumulative emissions of up to 2 teratons of carbon. For a given value of TCRE, we can estimate the estimated amount of warming expected over a future period in response to scenarios of cumulative carbon emission. The IPCC AR6 provides a *very likely* range for TCRE of 1.0–2.3°C, with a median value of 1.6°C.<sup>48</sup>

As will be discussed in Chapter 6 a real-world ECS below the model average is supported by studies which show climate models on average estimate too much warming at the surface and in the troposphere compared to observations over the past 50 years. Also it aligns with evidence from consistent fingerprinting (Section 7) that model responses to GHGs need to be scaled down quite a bit to align with observed trends.

## 5.6 Summary

In the past 5 years, there is a growing realization that climate models are not fit for the purpose of determining the sensitivity of the climate to increasing CO<sub>2</sub> (ECS), owing to the dependence of this sensitivity on poorly resolved processes related to clouds and water vapor.

Data-driven approaches using historical data and paleoclimate reconstructions are now regarded as more reliable for determining ECS, but their reliability is diminished by data inadequacies. The IPCC AR6 upper bound for the *likely* range of ECS is 4.0°C, lower than the AR5 value of 4.5°C. This lowering of the upper bound seems well justified by the paleoclimatic estimates of the ECS. The IPCC AR6 lower bound for the *likely* range of ECS is 2.5°C, substantially higher than the AR5 value of 1.5°C. This raising of the lower bound of the likely range of ECS has received a substantial challenge from the analysis of Lewis (2022, 2025) that finds the lower bound of the likely range to be 1.75°C with a median value of 2.16°C. Other lines of evidence supporting a lower bound on the ECS range below the IPCC AR6 value are discussed in Chapters 6 and 7.

Estimates of the transient climate response (TCR; TCRE) are more tightly constrained on the upper bound than the ECS.

Mauritsen, T., & Roeckner, E. (2020). Tuning the MPI-ESM1.2 global climate model to improve the match with instrumental record warming by lowering its climate sensitivity. *Journal of Advances in Modeling Earth Systems* 12, e2019MS002037; <https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2019MS002037>

Zelinka, M. D., Myers, T. A., McCoy, D. T., Po-Chedley, S., Caldwell, P. M., Ceppi, P., et al. (2020). Causes of higher climate sensitivity in CMIP6 models. *Geophysical Research Letters*, 47, e2019GL085782. <https://doi.org/10.1029/2019GL085782>

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<sup>i</sup> John J. Bates and Jeffrey L. Privette, “A Maturity Model for Assessing the Completeness of Climate Data Records,” *Eos, Transactions American Geophysical Union* 93, no. 44 (October 30, 2012): 441-441, <https://doi.org/10.1029/2012eo440006>.

<sup>ii</sup> Wendy S. Parker, “Confirmation and Adequacy-for-Purpose.”

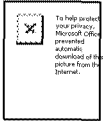
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**From:** Judith Curry <curry.judith@gmail.com>  
**Sent:** Thursday, May 8, 2025 5:55 PM  
**To:** Ross McKittrick  
**Subject:** Re: Ch 5 merged

I'm fine with nearly all of it, except for para on climate models. Any idea what happened to the references (they have been changed by someone to be Source 37, etc. If you know where these references are, i can send them, thx. Then i can have my person do the formatting, citations and refs

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**From:** Ross McKittrick [ross.mckittrick@gmail.com]  
**Sent:** 5/8/2025 8:32:42 PM  
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**Subject:** Ch 5 merged  
**Attachments:** 5 Climate Sensitivity.May1.Merged JCurry[RMcheck].docx

Took your suggestions and removed the chart.Â

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In 1979 the Charney (1979) Report for the US National Academy of Sciences proposed that the most likely value for ECS was 3.0°C plus or minus 1.5°C. With only minor variations this range was adopted and reaffirmed by the IPCC until the most recent AR6. The ECS range between 1.5 and 4.5°C is characterized by the IPCC AR5 as the *likely* range (66 percent probability); the AR5 stated that ECS is *extremely unlikely* (95 percent probability) to be below 1.0°C and very unlikely (90 percent probability) to exceed 6.5°C. This range of ECS values has remained stubbornly wide, despite many individual studies claiming to narrow it. Most recently, the IPCC AR6 narrowed its assessment of the *likely* range of ECS to 2.5–4.0°C and the *very likely* range to be between 2.0 and 5.0°C. This narrowing of the range on the low end is disputed, as will be discussed below.

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## 5.5 Transient Climate Response

The Transient Climate Response (TCR) is of greater utility in providing an observational constraint on climate sensitivity. TCR is the amount of warming that would occur at the time when CO<sub>2</sub> doubles, having increased gradually by 1 percent each year over a period of 70 years. Relative to the ECS, observationally-determined values of TCR avoid the problems of uncertainties in ocean heat uptake and the fuzzy boundary in defining equilibrium arising from a range of timescales for the longer-term feedback processes (e.g., ice sheets). TCR is more generally related to peak warming and better constrained by historical warming, than ECS. The IPCC AR6 judged the *very likely* range of TCR to be 1.2–2.4°C. **[source 47]** In contrast to ECS, the upper bound of the TCR is more tightly constrained. For comparison, the TCR values determined by Lewis (2023) is 1.25 to 2.0°C, showing much better agreement with the AR6 values than was seen in a comparison of the ECS values.

A related but more flexible parameter is the Transient Response to cumulative carbon Emissions, or TCRE, which relates global temperature change to the cumulative emissions. TCRE is based upon a linear relationship between global average temperature and cumulative emissions, which holds for cumulative emissions of up to 2 teratons of carbon. For a given value of TCRE, we can estimate the estimated amount of warming expected over a future period in response to scenarios of cumulative carbon emission. The IPCC AR6 provides a *very likely* range for TCRE of 1.0–2.3°C, with a median value of 1.6°C.<sup>48</sup>

As will be discussed in Chapter 6 a real-world ECS below the model average is supported by studies which show climate models on average estimate too much warming at the surface and in the troposphere compared to observations over the past 50 years. Also it aligns with evidence from consistent fingerprinting (Section 7) that model responses to GHGs need to be scaled down quite a bit to align with observed trends.

## 5.6 Summary

In the past 5 years, there is a growing realization that climate models are not fit for the purpose of determining the sensitivity of the climate to increasing CO<sub>2</sub> (ECS), owing to the dependence of this sensitivity on poorly resolved processes related to clouds and water vapor.

Data-driven approaches using historical data and paleoclimate reconstructions are now regarded as more reliable for determining ECS, but their reliability is diminished by data inadequacies. The IPCC AR6 upper bound for the *likely* range of ECS is 4.0°C, lower than the AR5 value of 4.5°C. This lowering of the upper bound seems well justified by the paleoclimatic estimates of the ECS. The IPCC AR6 lower bound for the *likely* range of ECS is 2.5°C, substantially higher than the AR5 value of 1.5°C. This raising of the lower bound of the likely range of ECS has received a substantial challenge from the analysis of Lewis (2022, 2025) that finds the lower bound of the likely range to be 1.75°C with a

median value of 2.16°C. Other lines of evidence supporting a lower bound on the ECS range below the IPCC AR6 value are discussed in Chapters 6 and 7.

Estimates of the transient climate response (TCR; TCRE) are more tightly constrained on the upper bound than the ECS.

Mauritsen, T., & Roeckner, E. (2020). Tuning the MPI-ESM1.2 global climate model to improve the match with instrumental record warming by lowering its climate sensitivity. *Journal of Advances in Modeling Earth Systems*, 12, e2019MS002037; <https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2019MS002037>

Zelinka, M. D., Myers, T. A., McCoy, D. T., Po-Chedley, S., Caldwell, P. M., Ceppi, P., et al. (2020). Causes of higher climate sensitivity in CMIP6 models. *Geophysical Research Letters*, 47, e2019GL085782. <https://doi.org/10.1029/2019GL085782>

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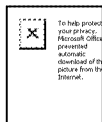
**From:** Judith Curry <curry.judith@gmail.com>  
**Sent:** Wednesday, May 7, 2025 9:19 AM  
**To:** Steven Koonin  
**Cc:** Travis Fisher; Ross McKittrick; Roy W. Spencer; John Christy  
**Subject:** Re: my review of Chapter 13

chiming in on ch 13. I really like this chapter. While it is more comprehensive than some of the chapters, the length isn't really out of line and its understandable to the nonexpert

On Tue, May 6, 2025 at 12:56 PM Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)> wrote:

See attached. More comments/questions than edits in this one.

SEK



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**From:** Steven Koonin [steven.koonin@gmail.com]  
**Sent:** 5/6/2025 7:56:22 PM  
**To:** 'Travis Fisher' [travis.scott.fisher@gmail.com]; 'Ross McKittrick' [ross.mckittrick@gmail.com]; 'Judith Curry' [curry.judith@gmail.com]; 'Roy W. Spencer' [roywspencer@hotmail.com]; 'John Christy' [climateman60@gmail.com]  
**Subject:** my review of Chapter 13  
**Attachments:** 13 Climate, Economy and SCC.May6[SEK].docx

See attached. More comments/questions than edits in this one.

SEK

## 13 Climate change, the economy and the Social Cost of Carbon

### 13.1 Climate change and economic growth

#### *13.1.1 Overview: climate is a relatively minor issue for a modern economy*

It has long been noted that economies tend to do poorly in very cold and very hot regions, with the optimum somewhere in between (Nordhaus 2006). Temperature-sensitive economic activity migrates, whenever possible, to where it is best suited, and society always adapts to the local climate. Based in part on these observations, in 1992 Thomas Schelling, then President of the American Economic Association, argued that any effects climate change on US economic activity would be small relative to the many other changes that would happen.

... Manufacturing rarely depends on climate, and where temperature and humidity used to make a difference, air conditioning has intervened. When Toyota chooses among Ohio, Alabama, and Southern California for locating an automobile assembly, geographical considerations are important, but not because of climate... Finance is little affected by climate; similarly for health care, or education, or broadcasting. Transportation can be affected, but improvements in all-weather landing and take-off in the last 30 years are greater than any differences that climate makes. If the average effect is a warming, iced waterways and snow removal may decline in importance. Construction is affected, mainly by cold, and if the average effect is in the direction of warming, construction may benefit slightly.

It is really agriculture that is affected. But even if agricultural productivity declined by a third over the next half century, the per capita GNP we might have achieved by 2050 we would achieve only in 2051. ...

**I conclude that in the United States, and probably Japan, Western Europe, and other developed countries, the impact on economic output will be negligible and unlikely to be noticed.**

(Schelling 1992, emphasis added)

Thirty years later virtually the identical point was made by the IPCC itself in the Fifth Assessment Report:

**For most economic sectors, the impact of climate change will be small relative to the impacts of other drivers.** Changes in population, age, income, technology, relative prices, lifestyle, regulation, governance, and many other aspects of socioeconomic development will have an impact on the supply and demand of economic goods and services that is large relative to the impact of climate change.

(Arent et al. 2014, emphasis added)

That statement is validated by experience. Since 1900, the average global surface temperature anomaly warmed 1.3°C, about as much as the IPCC predicts will occur in the next century under a moderate emissions scenario. But even as the globe warmed and the population quintupled, humanity prospered as never before. For example, global average lifespan went from thirty-two years to seventy-two years, economic activity per capita grew by a factor of seven, and the death rate from extreme weather events plummeted by a factor of fifty!

While extreme weather events are costly, in all modern economies they are becoming steadily less and less important (Formetta and Feyen 2019). Since 1990 weather-related disaster losses have declined as a proportion of global GDP (Pielke Jr 2018, 2020) as have mortality risks (Formetta and Feyen 2019). While economic weather-related insurance payouts are rising, this is fully explained by the growth in the size of the economy and the value of the insured asset stock. Past increases in episodes extreme weather have not had a significant effect (positive or negative) on the market value of insurance firms (Hu and McKittrick 2015). Nor have past extreme weather events had a significant effect on US banks' performance (Blickle et al. 2021).

For these reasons, economists have long been reluctant to endorse attempts to "stop" climate change or even aggressively reduce GHG emissions because the costs would not be worth it. As one critic of the economics of climate policy put it:

Mainstream climate economics takes global warming seriously, but perplexingly concludes that the optimal economic policy is to almost do nothing about it... The contrast is striking. While climate science is sending out loud-and-clear messages that fossil-fuel disinvestment must start now, letting go of coal and oil and diverting resources into renewable energy technology systems, to keep warming below the 2°C limit (IPCC 2014), mainstream climate economics claims that overly ambitious climate targets will unnecessarily hurt the economy and immediate de-carbonization is too expensive. Most climate economists thus recommend humanity to just wait-and-see.  
(Storm 2017)

The mainstream economics position on the climate policy question is best represented by the findings over the past three decades from Integrated Assessment Models (IAMs) of climate change policy, for which Yale economist William Nordhaus was awarded the 2018 Nobel Memorial Prize in economics. IAMs combine economic, climate, and social data into a unified framework for simulating climate damages and evaluating the optimal policy response (Resources for the Future 2025). Nordhaus' work has generally supported modest global climate policy, with aggressive measures largely deferred to later in the century. Nordhaus developed the so-called Dynamic Integrated Model of the Climate and Economy model, or DICE, in the early 1990s (Nordhaus 1993) to study the interaction between climate change, climate policy, and global economic growth over long times. DICE assumes global emission control can be coordinated at no cost and asks what the optimal policy target should be. The climate component of the DICE model is based on simplified climatological modeling. The version of DICE at the time of Nordhaus' Nobel Prize award was described in Nordhaus (2018); it had a climate sensitivity parameter of 3.1°C for CO<sub>2</sub> doubling, consistent with the best estimate in contemporary IPCC reports (3.0°C).

The baseline (no policy) scenario incurs only \$0.4T in global abatement costs and leads to \$134.2T (trillion dollars) in global climate damages for a total cost of \$134.6T. The climate model component of DICE projects 4.1°C warming by 2100 relative to preindustrial temperatures. Note that this is a higher estimate of warming than many IPCC climate models. (AR6 offers 2.7°C in 2100 under a moderate emissions scenario.)

The Optimal Policy scenario barely deviates from the business-as-usual path. It aims for +3.5°C warming, in other words we scale back only the lowest-value fossil fuel use and otherwise just live with almost all the warming. This suggests that most CO<sub>2</sub> emissions are less harmful than the policies that would be necessary to abate them. Trying to prevent warming causes costs quickly to outstrip the benefits. Pursuing a goal of capping warming at 2.5°C creates total costs of \$177.8T,

which is \$43.2T worse than doing nothing at all. Nordhaus didn't evaluate trying to reach a Paris-type target of 1.5°C warming but it would be even worse.

A subsequent edition of DICE includes higher assumed damages from warming which, not surprisingly leads to more aggressive policy recommendations, as explained in the section below on the Social Cost of Carbon.

### *13.1.2 Empirical analysis of climate change and economic growth*

Many other studies have used econometric methods instead of IAMs to look at the potential impact of climate change on economic growth. Dell et al. (2012, herein DJ012) was an influential study that used a multi-country panel of national-level data spanning 1950 to 2005, in which they matched climate and economic data by averaging temperature from the local grid cell level up to the national level using population weights. They found that warming yields an insignificant positive effect on income growth in rich countries but a significant negative effect in poor countries. Moore and Diaz (2015) modified the DICE model to take that finding into account and concluded that it implied a dramatically higher Social Cost of Carbon due to the compounding effects of income loss over time.

A large subsequent literature has debated the robustness of the DJ012 findings. Burke et al. (2015) analyzed a global panel with temperatures averaged up to the national level and found a negative effect on growth from warming in rich and poor countries alike when the national average temperature is above 13°C. Zhao et al. (2018) used the G-Econ data set of Nordhaus (2006), which breaks economic activity down to the grid cell level, replicated DJ012-type results on the same subset of countries as used in DJ012 but then showed that on the full global sample warming increases growth in rich countries and poor countries alike, though the positive effect in the latter group is confined to where local temperatures are below about 16°C. Greßer et al. (2021) developed a regional economic data set for 1,542 sub-national regions around the world between 2005 and 2015 and found temperature had no effect on growth. Yang et al. (2023) updated the DJ012 data set and applied an estimator robust to mixed sample frequencies, finding that while temperature shocks exerted a temporary effect on income levels, they did not have a significant lasting effect on growth rates.

Newell et al. (2021) noted that there is no underlying theory to guide econometric model specification in this literature. Taking into account the arbitrary choices of which explanatory variables to include they identified over 800 possible model specifications. Using the Burke et al. (2015) data they used an estimation method that accounts for model uncertainty and found that the model form preferred by Burke et al. (2015), which implied negative effects of warming on growth even in rich countries, is explicitly excluded by the optimal model selection algorithm. Overall they could not detect a temperature effect on GDP or GDP growth, and they estimated the 95% confidence interval for the impact on global growth as of 2100 even under the exaggerated RCP8.5 warming scenario spans -86 percent to +388 percent. In other words the net effect is likely positive but too uncertain to distinguish from zero.

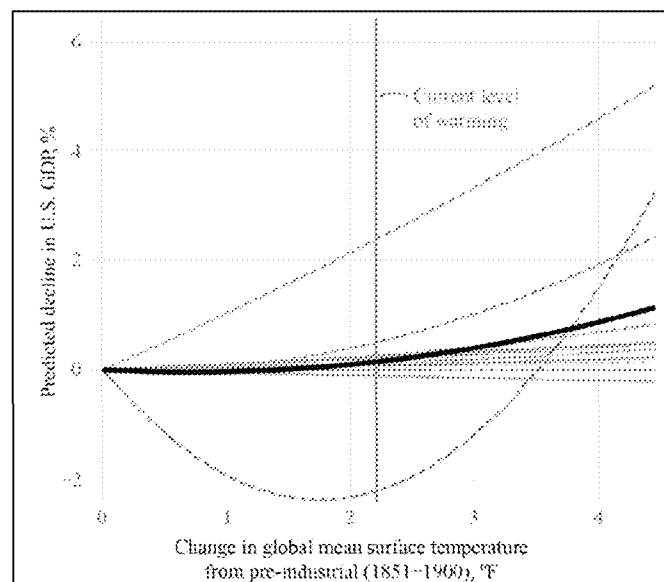
Barker (2023) criticized the DJ012 assumption that countries can be grouped into fixed “poor” and “rich” categories based on their incomes many decades ago. He noted that many countries were once poor but became rich over time, and if this is considered the original temperature effects reported by Dell et al. became small and insignificant.

Berg et al. (2023) argued that countries shouldn't be grouped into large Rich/Poor categories because they are too heterogeneous. They instead estimated country-specific temperature response coefficients then grouped countries with similar response coefficients into small panels. They

separately estimated responses to global and idiosyncratic local temperature shocks to better identify the climate signal in weather data. Overall they found countries experiencing negative effects of warming on growth outnumbered those experiencing positive effects, but only temporarily: eventually the effects reverse such that about twice as many countries experience a net positive growth effect. They also found global (as opposed to local) temperature changes are much more likely to benefit growth in poor countries than rich ones. In a simulation to 2100 even using the extreme RCP8.5 scenario they computed the average global GDP loss would be only 1.9% compared to a scenario with no warming. That is, instead of the economy growing 400% it would grow 398%. The implication of Nordhaus' analysis is that trying to prevent the warming would lead to far less than 398% growth.

To summarize, economists have long considered climate a relatively unimportant factor in economic growth, a view echoed by the IPCC itself in the Fifth Assessment Report. Mainstream climate economics has recognized that CO<sub>2</sub>-induced warming may have some negative economic effects but they are too small to justify aggressive abatement policy, and trying to “stop” or cap global warming even at levels well above the Paris target would be worse than doing nothing. An influential study in 2012 suggested that global warming would harm growth in poor countries but it has subsequently been found not to be robust. Studies that take full account of modeling uncertainties either find no evidence of a negative effect on global growth from CO<sub>2</sub> emissions or find poor countries as likely to benefit from it as rich countries.

The expectation that significant global warming would have a small impact on the U.S. economy was acknowledged quietly by the Biden Administration, even as the President was proclaiming a climate emergency. The following figure, from a 2023 OMB-CEA [report](#), shows the expected decrement in U.S. GDP as a function of temperature rise. The colored lines show the results of a dozen peer-reviewed published studies while the solid black line is their average. The figure could be summarized as “a few percent impact for a few degrees of warming”. Given that the economy’s annual growth rate is expected to be 1-2 percent, the impact of a warming globe is indeed negligible.



## 13.2 Models of the Social Cost of Carbon



The Social Cost of Carbon (SCC) is a tool for quantifying the economic impact of carbon dioxide emissions, helping policymakers weigh the costs and benefits of climate policies. It estimates the damage caused by emitting one additional ton of CO<sub>2</sub>, expressed in dollars. More formally, the SCC is the discounted present value of the current and future marginal loss of economic welfare due to an additional ton of CO<sub>2</sub> entering the atmosphere. On its own the SCC is not the appropriate price to attach to CO<sub>2</sub> emissions for the purpose of optimal emissions control but it can be converted into an optimal tax rate by scaling it by the Marginal Cost of Public Funds (MCPF). The theory behind this was first derived by Sandmo (1975) and has been reiterated many times since then by other economists working on the topic (e.g. Parry et al. 1999). The MCPF is the cost in terms of lost private economic welfare of raising public revenue by one dollar and always exceeds unity. If a jurisdiction does not use a carbon tax, this formula still indicates the upper bound on the amount emitters should spend on abatement options at the margin along the optimal policy path. Regulations should be imposed only insofar as they do not impose marginal abatement costs in excess of the optimal tax rate.

### *13.1.2 Estimating the SCC*

Although the literature refers to “estimates” of the SCC, it is not estimated in the way other economic statistics are estimated. For instance, data on market transactions including prices and quantities can be used to estimate the current inflation rate or the growth rate of per capita real Gross Domestic Product, and there are well-understood uncertainties associated with these quantities. But there are no market data available to measure many if not most of the marginal damages or benefits believed to be associated with CO<sub>2</sub> emissions, so these need to be imputed using economic models.

For example, an influential component of some SCC calculations is the perceived social cost associated with changed risk of future mortality due to extreme weather. There is no market in which people can directly attach a price to that risk. At best economists can try to infer such values by looking at transactions in related markets such as real estate or insurance, but isolating the component of price changes attributable to atmospheric CO<sub>2</sub> levels is very difficult.

Economists use IAMs to compute the SCC. Two of the best known IAMs are the Climate Framework for Uncertainty, Negotiation and Distribution (“FUND”, Tol 1997) and Nordaus’ DICE. IAMs embed a stylized global climate model with a very simplified representation of the global economy, including a “damage function” or set of functions relating ambient temperature to local economic conditions. The assumptions embedded in the damage function will largely determine the resulting SCC.

One approach to developing a damage function is to begin with estimates of the costs (or benefits) of warming in specific sectors in countries around the world and aggregate up to a global amount. This was the approach used in FUND. An alternative approach is to develop a simple equation that penalizes global income according to a simple quadratic function of the average global temperature. This approach was used in DICE. In the case of the FUND model many hundreds of parameters had to be selected, whereas in DICE only three were needed and were originally chosen to assign a predetermined penalty (1.2%) to global output as of 3°C warming, with a quadratic term implying that damages grow with the square of the global average temperature anomaly. Barrage and Nordhaus (2024) recently changed the parameters to increase the penalty at 3°C to 1.6%, and added a discrete additional 1.0% GDP penalty at 3°C warming to account for “tipping points” (discrete large-scale environmental changes triggered by crossing a warming threshold) and a “judgmental adjustment” of 0.5% for excluded impacts at 3°C warming. Not surprisingly the newer version of DICE generates much higher SCC estimates than before.

The concepts of estimation and uncertainty do not readily apply to SCC calculations. By comparison, the question of whether precipitation has trended up or down along the South Carolina coast for the past hundred years can be addressed by collecting rainfall data, estimating a trend parameter and calculating statistical confidence intervals using methods with well-understood mathematical properties. In this way uncertainty can, in principle, be resolved by collecting more data and applying more accurate methods. But no amount of data collection can change the fact that many components of the SCC are unknown and rely on judgment and opinion based on knowledge of the underlying literature on the physical effects of climate change.

SCC calculations are thus best thought of as “if-then” statements: *if* the following assumptions hold, *then* the SCC is \$X per tonne. The list of ‘if’ statements includes the premise that the world’s climate and economy work according to the representation in the IAM. One way this may fail to hold is in the timing of warming. Every IAM assumes a value of the Equilibrium Climate Sensitivity (ECS), controls the amount of warming that results from CO<sub>2</sub> emissions and can be freely varied for the purpose of generating a distribution of SCC values associated with uncertainties over ECS. But as Roe and Baumann (2013) pointed out, time-to-equilibrium increases with the square of ECS, so an upward adjustment of the ECS parameter without an appropriate slowing down of the adjustment process can yield distorted present value damage estimates. In particular, the upper tail of warming associated with some commonly-used ECS distributions is physically impossible for even a thousand years into the future (Roe and Baumann 2013) yet in an IAM would be realized within a couple of centuries. Failure to align ECS with time-to-equilibrium will lead to an overestimate of the SCC value.

### 13.2.2 Variations in the SCC

Every level of the IAM calculation includes assumptions, some more influential than others. Key assumptions include the following.

- The discount rate: Climate damages accrue over a long time horizon, and costs a century or two in the future need to be discounted to the present. The higher the discount rate the smaller the present value of future damages and vice versa. The discount rate represents the opportunity cost of spending money today rather than investing it and then having more to spend tomorrow. Some economists have argued for the use of very low discount rates in SCC calculations, resulting in policy recommendations that favor relatively large immediate investments in CO<sub>2</sub> emission reductions. The downside is that other investments could potentially earn a larger rate of return for society.
- Equilibrium Climate Sensitivity: IAMs have customarily employed a value of 3.0°C or 3.1°C following the IPCC’s guidance. Empirically-estimated ECS values tend to be lower than this (see Chapter XX). Dayaratna et al. (2017, 2020, 2023) have shown that use of lower empirically-derived ECS values dramatically lower the resulting SCC estimate, even when low discount rates are used.
- Damage function coefficients: IAMs assume CO<sub>2</sub> and warming cause net harms that increase exponentially with temperature. More recently, IAMs have also incorporated effects from assumed potential climate tipping points. The FUND model took limited but explicit account of CO<sub>2</sub> fertilization effects in agriculture. Since the coefficients were selected prior the publication of the current evidence of global greening and the magnitude of benefits to crops from elevated CO<sub>2</sub> (see Chapters 2 and 10) the growth effects are likely understated.

The DICE model (and others) did not explicitly include any CO<sub>2</sub> fertilization benefit, except to the extent it was taken into account in the literature consulted when picking the damage function coefficients. The damage function in FUND contains a region in which low warming yields net benefits in many regions, a finding which is supported by econometric models of warming and growth (Berg et al. 2023) and econometric simulations of agricultural changes (McKittrick 2025). The DICE damage function, by construction, rules out net benefits at any warming level.

- Emission scenarios: IAMs generate SCC estimates that increase as the pre-existing concentration of CO<sub>2</sub> increases. Consequently the value of damages later in the century will be higher, depending on the assumed baseline emissions over the coming decades.
- Abatement costs: IAMs represent the cost to the economy of reducing CO<sub>2</sub> emissions. If CO<sub>2</sub> emission reductions are assumed to be inexpensive, then the model will conclude that the optimal policy should aim for deeper emission cuts and vice versa.

It is informative to ascertain whether SCC results are invariant to changes in some assumptions. But when different assumptions result in higher or lower SCC values, the change in the SCC value does not provide *prima facie* evidence about the validity of the assumptions. For example, in 2023 the US Environmental Protection Agency raised its preferred SCC value about 5-fold over the estimates it had issued ten years earlier. This is not because new data had been collected or better mathematical methods had been invented, but because new assumptions had been used, and the validity of those assumptions was a separate question. One was that global agricultural damages were far higher than previously assumed, based on an analysis in Moore et al. (2017). But as discussed in Section XX, McKittrick (2025) showed that Moore et al. (2017) had used a database in which half the CO<sub>2</sub> change observations were missing. When as many of those observations as possible were recovered from underlying sources and the analysis was rerun, the projected crop yield losses disappeared and turned into gains at all warming levels. Hence the portion of the EPA's SCC revision attributable to agricultural yield losses was unwarranted.

### 13.2.3 Evidence for low SCC

Chapter 2 reviewed evidence on climate change and greening, and Chapter 10 looked at climate change and US agriculture. Evidence shows that CO<sub>2</sub> fertilization has a stronger beneficial effect on agriculture than was known at the time that IAMs like DICE and FUND were parameterized. In particular Haverd et al. (2020) found the observed CO<sub>2</sub> fertilization rate has been almost double what had been predicted by crop models. Dayaratna et al. (2023) used the updated empirical ECS distribution estimate of Lewis (2022), which assimilates modern instrumental and paleoclimatic temperature records, and allowed for a 30 percent gain in the CO<sub>2</sub> fertilization benefit in the FUND model, and found that, even at a low discount rate of 2.5 percent, the median SCC as of 2050 is only \$18.67, with a 24 percent probability of the true value being negative. At a five percent discount rate the median SCC value is negative until the mid-2040s and at 2050 was only \$0.37 with a 49 percent probability of being negative. Thus, under reasonable assumptions a mainstream IAM using updated scientific inputs yields evidence consistent with the SCC not being significantly greater than zero.

It should also be noted that the SCC is focused on the social costs of CO<sub>2</sub> emissions from fossil fuel use. It does not measure the private marginal benefits to consumers and society from the availability of fossil fuels. Public willingness to pay for fuels of all types indicates the value to society of reliable, abundant fossil energy. Tol (2017) estimates that the private benefit of carbon is

large relative to the social cost. This can be illustrated by noting that the price of a gallon of gas indicates the marginal value to the consumer of the fuel. Suppose we assume a relatively high Social Cost of Carbon of, say, \$75 per tonne. Deflated by a MCPF value of 1.5 that would result in a carbon tax of \$50 per tonne, which equates to about 44 cents per gallon of gas (Lavelle 2019). A pre-tax price of \$3.00 per gallon would imply the marginal social benefit of the fuel is nearly seven times the marginal social cost.

### 13.3 Summary

It is increasingly being argued that the SCC is too variable to be useful for policymakers. Cambridge Econometrics (Thoung 2017) stated it's "time to kill it" due to uncertainties. The UK and EU no longer use SCC for policy appraisal, opting for "target-consistent" carbon pricing (UK Department for Energy Security and Net Zero 2022, Dunne 2017). However the weaknesses of the SCC concept don't mean that other regulatory measures are inherently better or more efficient. Many climate regulations (such as electric vehicle mandates, renewable energy mandates, energy efficiency regulations and bans on certain types of home appliances) end up costing far more per tonne of abatement than a simple price on carbon emissions.

In summary, SCC estimates are highly uncertain due to unknowns in future economic growth, socioeconomic pathways, discount rates, climate damages, and system responses. The SCC is not intrinsically informative as to the economic or societal impacts of climate change. It provides an index connecting large networks of assumptions about the climate and the economy to a dollar value. Some assumptions yield a high SCC and others yield a low or negative SCC. The evidence for or against the underlying assumptions needs to be established independently; the resulting SCC adds no additional information about the validity of those assumptions.

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**From:** Judith Curry <curry.judith@gmail.com>  
**Sent:** Thursday, May 1, 2025 6:28 PM  
**To:** Roy Spencer  
**Cc:** Steven Koonin; Travis Fisher; Ross McKittrick; John Christy  
**Subject:** Re: May 1 status update

Looks good to me

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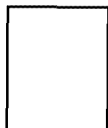
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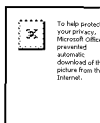
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**From:** John Christy [climateman60@gmail.com]  
**Sent:** 5/1/2025 9:45:42 PM  
**To:** Ross McKittrick [ross.mckittrick@gmail.com]  
**Subject:** Re: May 1 status update  
**Attachments:** PacCoast\_Prcp\_20241231.xlsx

Ross

Here is Pacific Coast. 29 stations along the coast. Continuous data for all stations begin on 1 Jan 1893 (first tab). I actually have data back to 1850 for SF which captures the 1861-62 ArkStorm, but the file's second tab begins with 1877.

I've looked at heaviest 5-day totals and don't see any tendency for more and/or stronger Atmospheric Rivers.

John C.

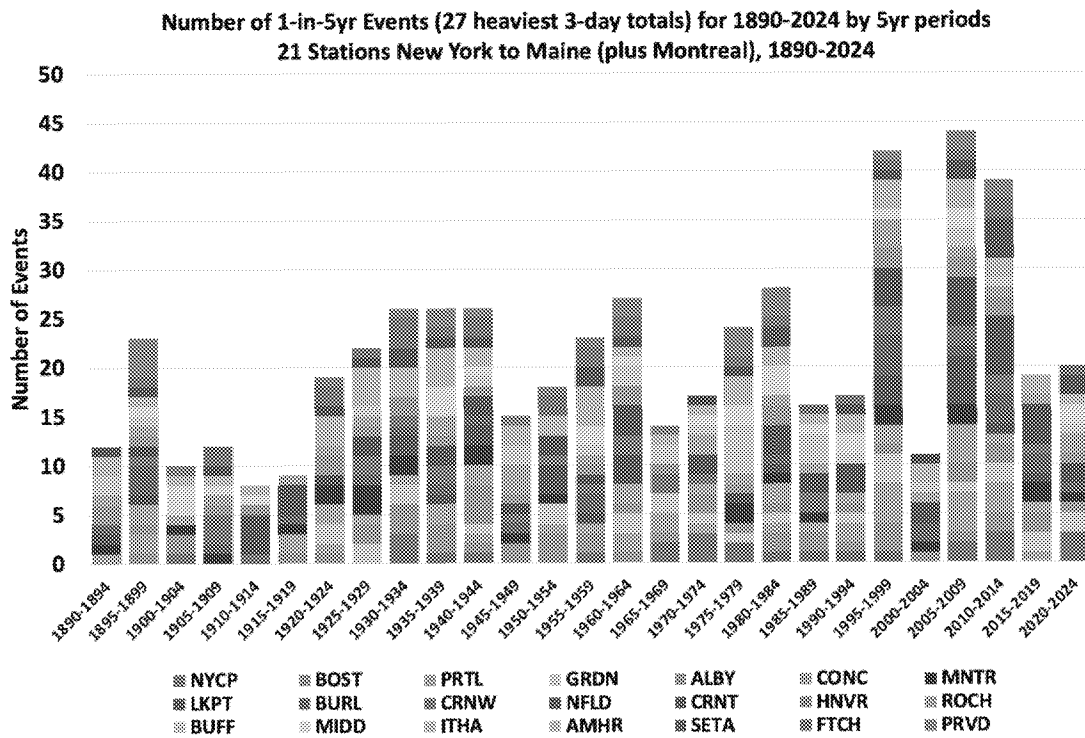
On Thu, May 1, 2025 at 4:18 PM John Christy <[climateman60@gmail.com](mailto:climateman60@gmail.com)> wrote:

Ross

I'll get started writing those sections and hunt for the Pacific data to send. The NCA made a big deal of the increase in extreme precip events in the Northeast. I've generally been able to reproduce their results with the 21 stations I've put together (including Montreal). This was a pain as there were many issues with the data, but I've scrubbed it more carefully than any dataset used in the NCA. These daily data start 1 Jan 1888 and are complete to 31 Dec 2024. Attached is a figure that supports the idea that extreme events are increasing there. NCA liked the statistic of heaviest 1-in-5yr event of 2 or 3-day totals which means in 135 years (1890-2024) there are 27 "extreme" events to distribute through time. Note that 3 of the 5-year bins are very high thanks to a clustering of tropical systems that hit the Northeast in those periods (heavy events are dominated by the summer-fall timeframe when tropical systems die up there).

I'm sure you have some words about the fact that precipitation events are not gaussian in time or space and thus clustering of events is commonly found - and you probably have some statistical tests to determine the relevance of clustering for future projections. Too, having only 135 years is a tiny sample of the patterns that the atmosphere/ocean system can generate, so weird things actually happen all the time somewhere.

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**From:** Steven Koonin [steven.koonin@gmail.com]  
**Sent:** 5/1/2025 8:02:48 PM  
**To:** 'Roy Spencer' [roywspencer@hotmail.com]; 'Travis Fisher' [travis.scott.fisher@gmail.com]; 'Judith Curry' [curry.judith@gmail.com]  
**CC:** 'Ross McKittrick' [ross.mckittrick@gmail.com]; 'John Christy' [climateman60@gmail.com]  
**Subject:** RE: May 1 status update  
**Attachments:** image001.jpg

I'd add the following points

- The report relies on UN, USG assessments, as well as the peer-reviewed research literature and primary observational data.
- I [Chris] have scrutinized the report and then met with the team to ask some tough questions about it. On that basis, I believe they've done a fine job.
- Nevertheless, non-expert readers will likely be surprised by what the report says since it is at variance with the prevailing "climate crisis" narrative. To my mind, that's a measure of how severely things have been misrepresented
- Because it is so important to accurately portray the certainties and uncertainties of climate science, I am opening the draft report up to public comment. Open substantial scientific debate has been sorely absent from climate science and this is an opportunity to restore that missing.

---

**From:** Roy Spencer <roywspencer@hotmail.com>  
**Sent:** Thursday, May 1, 2025 3:43 PM  
**To:** Steven Koonin <steven.koonin@gmail.com>; 'Travis Fisher' <travis.scott.fisher@gmail.com>; 'Judith Curry' <curry.judith@gmail.com>  
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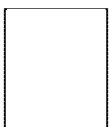
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**From:** Steven Koonin [steven.koonin@gmail.com]  
**Sent:** 5/1/2025 7:37:42 PM  
**To:** 'Travis Fisher' [travis.scott.fisher@gmail.com]; 'Judith Curry' [curry.judith@gmail.com]  
**CC:** 'Ross McKittrick' [ross.mckittrick@gmail.com]; 'Roy W. Spencer' [roywspencer@hotmail.com]; 'John Christy' [climateman60@gmail.com]  
**Subject:** RE: May 1 status update  
**Attachments:** ~WRD1823.jpg

Off the top of my head, here are a few points the Secretary's cover letter might make. I'm sure others can refine these or add a few more - SEK

- Good energy policy making requires a complete and accurate picture of the state of climate science
- I [Chris] have long been a student of climate science. My technical background has allowed me to read the IPCC, USG assessment reports, as well as some of the original literature, and have substantial conversations with a variety of climate scientists
- I have seen first hand how the media and political coverage imperfectly reflects, if not distorts' the state of the science, to the point where non-experts usually have it very wrong – “the science doesn't say what you think it says”
- To remedy the situation, I commissioned an independent team of credentialed experts to summarize the state of the science, with particular emphasis on the question of whether GHG emissions endanger the US population
- I have long respected scientific integrity and so have exerted no control or influence over what the team wrote – what you are reading are their own words
- ...

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**From:** Travis Fisher <travis.scott.fisher@gmail.com>  
**Sent:** Thursday, May 1, 2025 2:14 PM  
**To:** Judith Curry <curry.judith@gmail.com>  
**Cc:** Ross McKittrick <ross.mckittrick@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; John Christy <climateman60@gmail.com>; Steven Koonin <steven.koonin@googlemail.com>  
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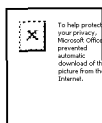
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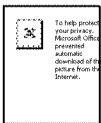
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**Subject:** Re: May 1 status update  
**Attachments:** Sea level (1).docx; heat\_cold mortality (1).docx; climate sensitivity JC text.docx

Hello I've emailed last week the sea level rise and heat/cold mortality sections, I even think i put them in some folder. Here they are again, I would appreciate comments/suggestions. Also included is my version of Climate sensitivity (in case that one got lost also).

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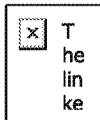
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## 8 Changes in Sea level

Arguably the most important climate impact driver that is unambiguously associated with increasing temperatures is global sea level rise. Global warming increases sea level rise through thermal expansion of the volume of sea water and melting of glaciers and ice sheets. Another factor that influences sea level variations is land water storage. Regional sea level change is influenced by large-scale ocean circulation patterns, and geologic processes and deformation from the redistribution of ice and water. Local sea level rise is further influenced by vertical land motion from geologic processes, ground water withdrawal, and fossil fuel extraction.

The IPCC AR6 estimates that global mean sea level increased by 7.9 (5.9–9.8) inches between 1901 and 2018. The rate of sea level rise has accelerated in recent decades. At the ocean basin scale, sea levels have risen fastest in the Western Pacific and slowest in the Eastern Pacific over the period 1993–2018.<sup>1</sup> The rate of global sea level rise is estimated to be 0.12 inches/year (for reference: 0.12 in is the height of two stacked pennies).<sup>2</sup>

The observing systems for global sea level rise have advanced significantly in the satellite era, particularly with the advent of satellite altimeters since 1993. Local tide gauges have provided useful data for the past century, and even longer for a few locations. Following the end of the Little Ice Age in the mid-nineteenth century, tide gauges show that the global mean sea level began rising during the period 1820–1860.

### 8.1 U.S. coastal sea level rise

Observed and predicted rates of mean global sea level rise may have little relevance for specific locations<sup>3</sup>. In Canada and Alaska (and also northern Washington), sea level is actually decreasing, owing to uplift from glacial rebound. Most of the Pacific coast has rates of sea level rise of 0 to 0.12 inches/year. The largest rates of sea level rise are on the Gulf coast (Louisiana and Texas) and in the mid-Atlantic states (Chesapeake Bay region).

Measurements of relative sea level rise from tide gauges conflate the rise in the volume of seawater with local vertical land motion. Hence in examining local sea level changes, it is important to also consider the local vertical land motion. Absolute local sea level rise is the sum of relative sea level rise and the local vertical land motion.

A wide range of processes can cause vertical land motion along the coasts, having amplitudes comparable to the sea level signals expected from land-ice melting or ocean thermal expansion. Vertical land motion on the coasts can locally exacerbate (subsidence/sinking) or mitigate (uplift) the risk of sea level rise. Local changes in sea level vary considerably from place to place and can

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<sup>1</sup> B. Fox-Kemper et al., “Ocean, Cryosphere and Sea Level Change,” in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Geneva, CH: Intergovernmental Panel on Climate Change, 2021), 1211-1362.

<sup>2</sup> “Rising Waters: How NASA Is Monitoring Sea Level Rise,” NASA (NASA), accessed May 19, 2022, <https://www.nasa.gov/specials/sea-level-rise-2020/>.

<sup>3</sup> <https://tidesandcurrents.noaa.gov/sltrends/>

deviate substantially from the rate of global mean sea level change.<sup>4</sup> Human activities triggering subsidence are soil drainage (e.g. for urban development purposes) or subsurface mining of resources such as groundwater, oil or gas. The magnitude of relative sea level rise caused by human activities is often considerable. Local vertical land motion of relevance to local sea level change is best measured using a Global Positioning System (GPS) station located in the location as the tide gauge.

Table 8.1 shows absolute sea-level rise (ASLR) for selected locations, determined from the sum of uncorrected sea-level rise as estimated from tide gauge time series (RSLR)<sup>5</sup> and the vertical land motion (VLM)<sup>6, 7,8</sup> measurements. The absolute sea level rise for each of these locations is significantly smaller than the measured relative sea level rise owing to local sinking of the land. More than half of the measured relative sea level rise is attributed to land sinking for these locations: San Francisco, Galveston, Grand Isle. For reference, the global average rate of absolute sea level rise is estimated to be 0.12 inches/year.

**Table 8.1** Absolute sea level rise (inches/year) (RSLR plus VLM)

| Location          | RSLR  | VLM   | ASLR  |
|-------------------|-------|-------|-------|
| San Francisco, CA | +0.08 | -0.06 | +0.02 |
| Galveston, TX     | +0.26 | -0.19 | +0.07 |
| Grand Isle, LA    | +0.36 | -0.28 | +0.08 |
| St Petersburg, FL | +0.12 | -0.02 | +0.10 |
| New York City, NY | +0.11 | -0.05 | +0.06 |

### *San Francisco Bay*

Over the past 100 years, relative sea level in the San Francisco Bay area has risen by 7.8 inches, at an average rate of 0.08 inches/year (Figure 8.1). As shown in Table 6.1, San Francisco's vertical land motion is -0.06 inches/year (sinking), producing a recent rate of absolute sea level rise of +0.02 inches/year. Portions of Treasure Island, San Francisco International Airport, and Foster City are sinking as fast as 0.4 inches/year.<sup>9</sup> Landfill zones are sinking due to soil compaction, at a rate as much as one-half inch per year, threatening coastal infrastructure including the San Francisco International Airport. The problems in the San Francisco Bay area have been caused primarily by sinking in landfill regions that were formerly wetlands, not by the slow creep of global sea level rise.

<sup>4</sup> Wöppelmann, G., and M. Marcos (2016), Vertical land motion as a key to understanding sea level change and variability, *Rev. Geophys.*, 54, 64–92.

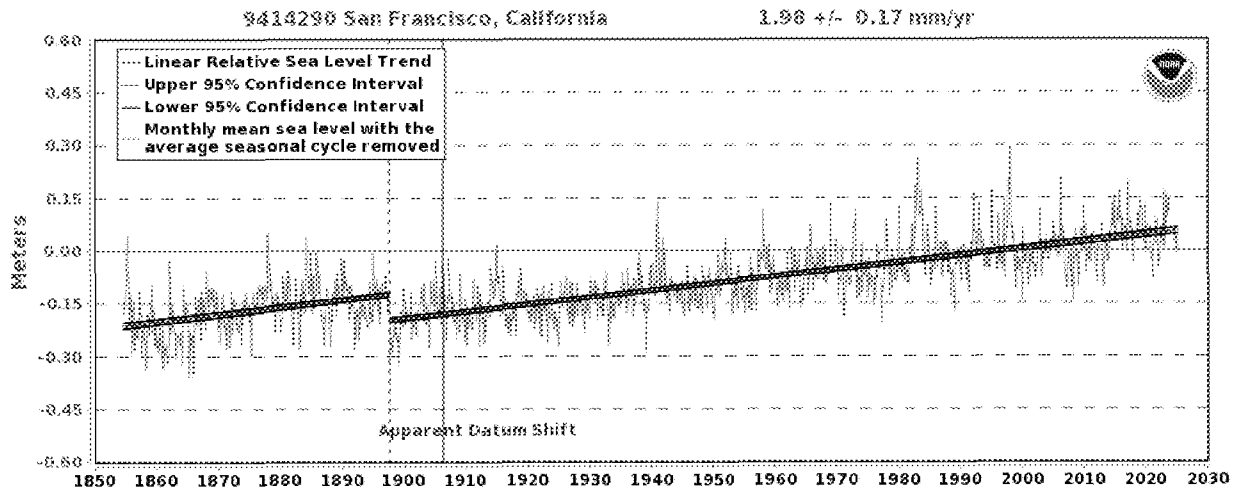
<sup>5</sup> NOAA Tides & Currents, Relative Sea Level Trends - <https://tidesandcurrents.noaa.gov/sltrends/>

<sup>6</sup> NAS (2012) *Sea-Level Rise for the Coasts of California, Oregon and Washington: Past, Present, and Future*. Appendix A: Vertical Land Motion and Sea-Level Data Along the West Coast of the United States. National Academies Press, NAP.edu/10766.

<sup>7</sup> Letetrel, C, M Karpytchev, MN Bouin et al (2015) Estimation of vertical land movement rates along the coasts of the Gulf of Mexico over the past decades. *Continental Shelf Research*, 111, 42-51.

<sup>8</sup> Karegar, MA, TH Dixon, SE Engelhart (2016), Subsidence along the Atlantic Coast of North America: Insights from GPS and late Holocene relative sea level data, *Geophys. Res. Lett.*, 43, 3126–3133, doi:10.1002/2016GL068015.

<sup>9</sup> Shirzaei, M, R Burgmann (2018) Global climate change and local land subsidence exacerbate inundation risk to the San Francisco Bay Area. *Science Advances*, 4, eaap9234



**Figure 8.1.** Tide gauge measurements at San Francisco, California, obtained from NOAA - [https://tidesandcurrents.noaa.gov/sltrends/sltrends\\_station.shtml?id=9414290](https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=9414290) (downloaded 4/22/25).

### *Galveston - Houston*

Long-term tide measurements at Galveston Pier 21 show sea level rise of 2.18 feet in the past century, or a rate of 0.26 inches/year (Figure 8.2). Vertical land motion (subsidence) at Galveston is estimated at -0.19 inches/year, yielding a value of absolute sea level rise of +0.07 inches/year (Table 8.1). The U.S. Geologic Survey found that most of the land-surface subsidence in the Houston-Galveston region has occurred as a direct result of groundwater withdrawals.<sup>10</sup> This caused compaction of the aquifer sediments, mostly in the fine-grained silt and clay layers. By 1979, as much as 10 feet of subsidence had occurred in Houston.

Hurricanes are traditionally the major concern in the region. The 1900 hurricane that struck Galveston and killed between 6,000 and 12,000 people is still considered the United States' deadliest natural disaster.<sup>11</sup> Hurricane Ike (2008) decimated large portions of the Bolivar Peninsula literally removing significant portions of the land mass.<sup>12</sup> While only 17 people were killed in Texas, property damage exceeded \$50 billion.<sup>13</sup> In 2017, Hurricane Harvey struck the region, bringing catastrophic rainfall-triggered flooding that inflicted over \$125 billion in damages.<sup>14</sup>

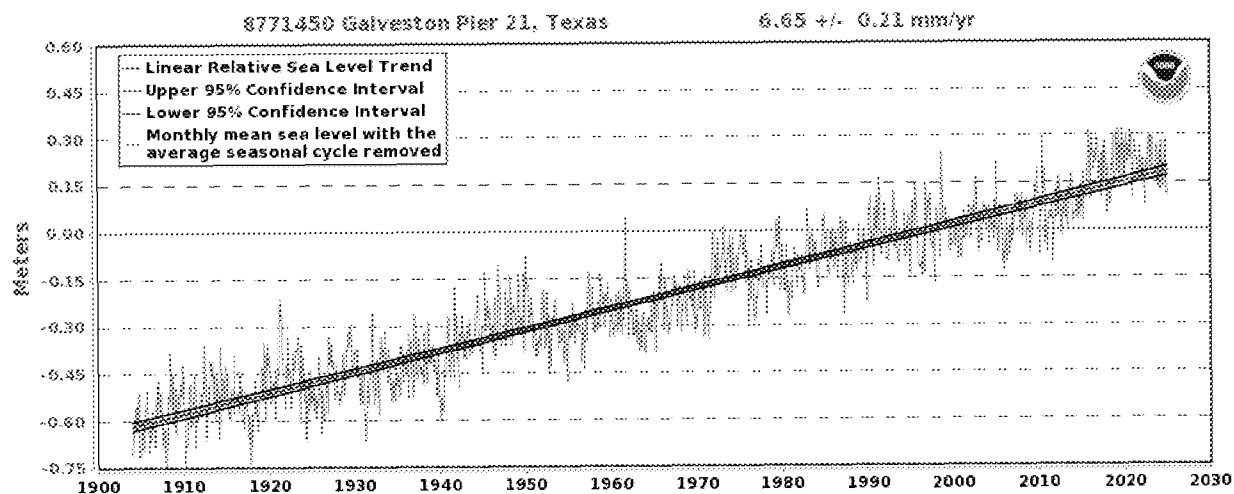
<sup>10</sup> Kasmarek, M.C., and Ramage, J.K., 2017, Water-level altitudes 2017 and water-level changes in the Chicot, Evangeline, and Jasper aquifers and compaction 1973–2016 in the Chicot and Evangeline aquifers, Houston-Galveston region, Texas: U.S. Geological Survey Scientific Investigations Report 2017–5080, 32 p., <https://doi.org/10.3133/sir20175080>.

<sup>11</sup> Weems, John Edward, "Galveston Hurricane of 1900", Texas State Historical Association, (March 15, 2016) <https://www.tshaonline.org/handbook/entries/galveston-hurricane-of-1900>.

<sup>12</sup> "Galveston County, Texas, Faces Sea Level Rise and Storms", Union of Concerned Scientists, (June 23, 2017) <https://www.ucs.org/resources/galveston-county-texas-faces-sea-level-rise-and-storms>.

<sup>13</sup> White, Audrey, "Galveston Still Healing 5 Years After Hurricane Ike", The Texas Tribune, (April 26, 2013) <https://www.texastribune.org/2013/04/26/galveston-still-healing-5-years-after-hurricane-ike/>.

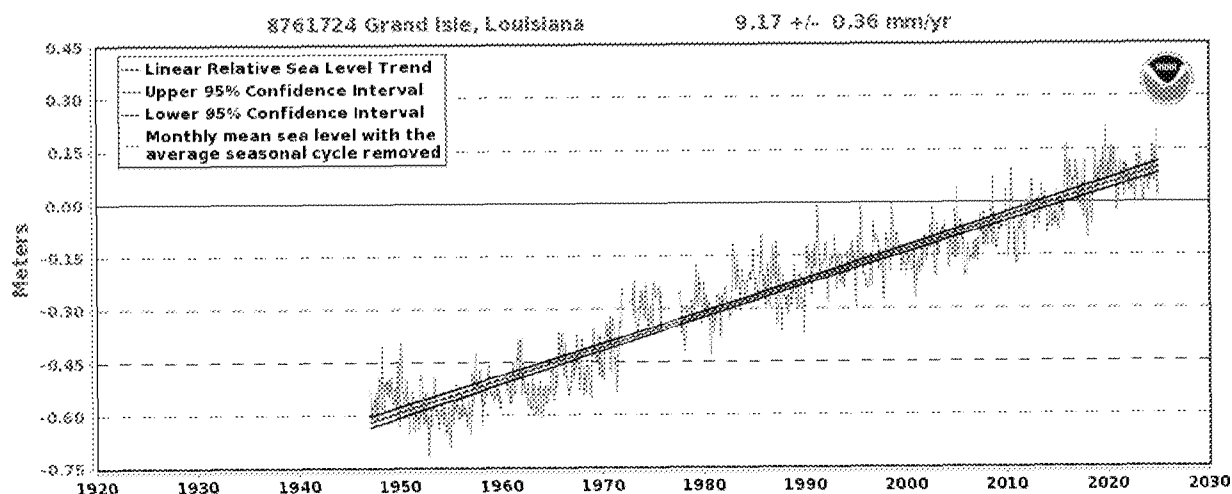
<sup>14</sup> NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2025). <https://www.ncei.noaa.gov/access/billions/>, DOI: 10.25921/stkw-7w73



**Figure 8.2.** Tide gauge measurements Galveston Pier, TX, obtained from NOAA - [https://tidesandcurrents.noaa.gov/sltrends/sltrends\\_station.shtml?id=8771450](https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8771450) (downloaded 4/22/2025).

### *New Orleans and the Mississippi delta*

There are long-term tide gauge measurements at Grand Isle, Louisiana, respectively estimating that sea level has risen slightly more than 3 feet over the last 100 years and at an average rate of 0.36 inches/year (Figure 8.3). Vertical land motion (subsidence) is estimated -0.28 inches/year at Grand Isle. From Table 6.1, the absolute sea level rise is +0.08 inches/year at Grand Isle.



**Figure 8.3.** Tide gauge measurements at Grand Isle, LA, obtained from NOAA - [https://tidesandcurrents.noaa.gov/sltrends/sltrends\\_station.shtml?id=8761724](https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8761724) (downloaded 4/22/25).

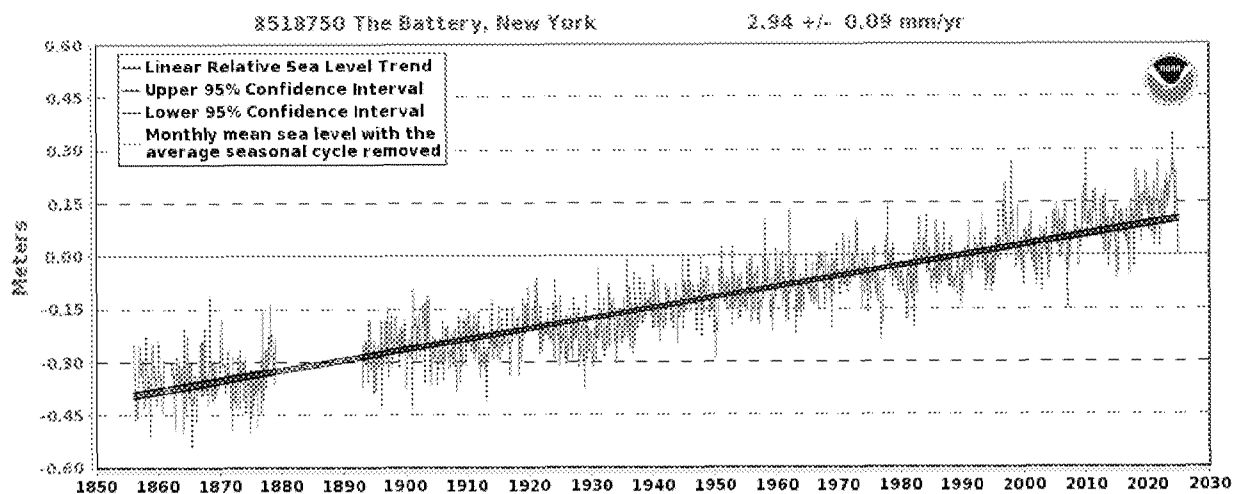
The issues of sea level rise and land loss in the Mississippi delta region are complex, with geological subsidence and the decline in sediment transported by the Mississippi river being the dominant drivers. Due to the construction of dams in the basin since the 1950s, the suspended



sediment load of the Mississippi River has decreased by ~50%.<sup>15</sup> A new subsidence map of coastal Louisiana finds the coastal region to be sinking at about one third of an inch per year.<sup>16</sup> For a city whose elevation averages one to two feet below sea level, sea level rise from human caused warming is not the dominant driver for the problems that New Orleans is facing.

### *New York City*

New York City is particularly vulnerable to the effects of sea level rise because it is built primarily on islands and has 520 miles of coastline. In New York City, relative sea level has risen over 11 inches over the past century, at an average rate of 0.11 inches/year (Figure 8.4). Vertical land motion in the New York City area is occurring at a rate of -0.05 inches/year (subsidence), corresponding to roughly 5 inches per century. From Table 6.1, the absolute rate of sea level rise at The Battery location is 0.06 inches/year, or about 55% of the measured relative sea level rise.



**Figure 8.4.** Tide gauge measurements at The Battery, New York, obtained from NOAA - [https://tidesandcurrents.noaa.gov/sltrends/sltrends\\_station.shtml?id=8518750](https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8518750) (downloaded 4/22/25).

Following Hurricane Sandy, New York has developed a comprehensive plan: *City of New York: Building a Stronger, More Resilient New York*.<sup>17</sup> A broad range of coastal protection measures are outlined that match the risks facing a given area: increase coastal edge elevations, minimize upland wave zones, infrastructure to protect against storm surge, improve coastal design and governance, restore estuaries wetlands, coastal nourishment, site elevation, and drainage systems.

<sup>15</sup> Jillian M. Maloney et al., “Mississippi River Subaqueous Delta Is Entering a Stage of Retrogradation,” *Marine Geology* 400 (June 2018): 12–23, <https://doi.org/10.1016/j.margeo.2018.03.001>.

<sup>16</sup> Jaap H. Nienhuis et al., “A New Subsidence Map for Coastal Louisiana,” *GSA Today* 27, no. 6 (June 2017): 28–29, <https://doi.org/10.1130/GSATG337GW.1>.

<sup>17</sup> City of New York, *A Stronger, More Resilient New York* (New York: City of New York, June 2013), [http://s-media.nyc.gov/agencies/sirr/SIRR\\_singles\\_Hi\\_res.pdf](http://s-media.nyc.gov/agencies/sirr/SIRR_singles_Hi_res.pdf).

## 8.2 Sea level rise projections

The concern over sea level rise is not about the 8 inches or so that global mean sea level has risen since 1900. Rather, the concern is about projections of 21<sup>st</sup> century sea level rise based on climate model-based projections of human-caused global warming.

The IPCC AR6 finds that there is *high agreement* across published global mean sea level projections for 2050 and there is little sensitivity to emissions scenarios. Considering only projections incorporating ice-sheet processes in whose quantification there is at least *medium confidence*, the global sea level projections for 2050, across all emissions scenarios, fall between 3.94 and 15.75 inches (5th–95th percentile *very likely* range) relative to the 1995–2014 baseline period.<sup>18</sup>

Conversely, there is *low agreement* across published global mean sea level projections for 2100, particularly for higher emissions scenarios. Considering only projections representing processes in whose quantification there is at least *medium confidence*, the AR6 global mean sea level projections for 2100 lie between 7.87 and 39.37 inches (5th–95th percentile *very likely* range) under the medium emissions scenario SSP2–4.5.<sup>19</sup> There is deep uncertainty surrounding projections of sea level rise to 2100, particularly for the higher emissions scenarios.

In evaluating the IPCC AR6 projections to 2050 (with reference to the baseline period 1995–2014), almost half of the sea level rise has already occurred by 2025. From the tide gauge measurements in Figures 8.1–8.4, there is no obvious acceleration in sea level rise beyond the historical average rate of sea level rise.

## 8.3 Summary

Since 1900, global sea level has risen by about 8". Sea level change along U.S. coasts is highly variable, associated with local variations in processes that contribute to sinking and also ocean circulation patterns. The highest levels of sea level rise along U.S. coasts are Galveston, New Orleans, and the Chesapeake Bay regions – each of these locations is associated with substantial local sinking that is unrelated to climate change.

Extreme projections of global sea level rise are associated with the implausible extreme emissions scenario and inclusion of poorly understood processes associated with hypothesized ice sheet instabilities. In evaluating the IPCC AR6 projections to 2050 (with reference to the baseline period 1995–2014), almost half of the sea level rise has already occurred by 2025 and at a lower rate than predicted. From the tide gauge measurements in Figures 8.1–8.4, there is no obvious acceleration in sea level rise beyond the historical average rate of sea level rise.

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<sup>18</sup> B. Fox-Kemper et al., “Ocean, Cryosphere and Sea Level Change,” in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Geneva, CH: Intergovernmental Panel on Climate Change, 2021), 1211–1362.

<sup>19</sup> B. Fox-Kemper et al., “Ocean, Cryosphere and Sea Level Change.”

## 2.3 Mortality risks from heat and cold extremes

The greatest confidence for impacts from global warming is an increase in extreme heat events and a decrease in extreme cold events; this has been observed in the historical period and is also expected with continued warming.

Mortality from heat extremes is typically caused by heat stroke and heat exhaustion. Mortality from cold extremes is typically caused by hypothermia and heart strain. It is well known that global mortality is substantially greater for extreme cold than for extreme heat.<sup>1,2</sup>

Specifically with regards to the U.S., extreme heat and extreme cold both kill hundreds of people each year.; however, different approaches to assessing heat/cold mortality produces different results. The Center for Disease Control (CDC) National Center for Health Statistics Compressed Mortality Database, which is based on death certificates, indicates that about twice as many people die of “excessive cold” conditions in a given year than of “excessive heat.”<sup>3,4</sup>

A 2015 epidemiological study of deaths in published in *The Lancet* found that cold-related deaths in the U.S. were about a factor of fifteen higher than heat-related deaths.<sup>5</sup> However, the study did not adjust for the seasonal cycle in mortality rates, which tend to increase during the winter months due to non-weather factors like influenza.<sup>6</sup> A more recent paper found that 86% of temperature-related deaths in the U.S. are due to cold-related mortality.<sup>7</sup>

The IPCC AR6 Working Group 2 Chapter 16.2.3.5 states how heat-related mortality is declining over time:<sup>8</sup>

“Heat-attributable mortality fractions have declined over time in most countries owing to general improvements in health care systems, increasing prevalence of residential air

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<sup>1</sup> Qi Zhao et al., “Global, Regional, and National Burden of Mortality Associated with Non-Optimal Ambient Temperatures from 2000 to 2019: A Three-Stage Modelling Study,” *The Lancet Planetary Health* 5, no. 7 (July 2021), [https://doi.org/10.1016/s2542-5196\(21\)00081-4](https://doi.org/10.1016/s2542-5196(21)00081-4).

<sup>2</sup> <https://ourworldindata.org/part-one-how-many-people-die-from-extreme-temperatures-and-how-could-this-change-in-the-future>

<sup>3</sup> Brett R. Scheffers et al., “The Broad Footprint of Climate Change from Genes to Biomes to People,” *Science* 354, no. 6313 (November 11, 2016): aaf7671, <https://doi.org/10.1126/science.aaf7671>.

<sup>4</sup> Rachel H. Alinsky, Scott E. Hadland, J. Deanna Wilson, Pamela A. Matson, and Brendan Saloner, “Trends in Polysubstance Overdose Deaths Involving Opioids, Stimulants, and Benzodiazepines by Race and Ethnicity in the US, 2007-2021,” *JAMA Network Open* 7, no. 3 (March 2024): e238249, <https://doi.org/10.1001/jamanetworkopen.2024.8249>.

<sup>5</sup> Lancet Commission on Climate and Health, “Health and Climate Change: Policy Responses to Protect Public Health,” *The Lancet* 386, no. 10006 (November 7, 2015): 1861–1914, [https://doi.org/10.1016/S0140-6736\(15\)60854-6](https://doi.org/10.1016/S0140-6736(15)60854-6).

<sup>6</sup> Bob Henson, “Which Kills More People: Extreme Heat or Extreme Cold?” *Weather Underground*, January 22, 2019, <https://www.wunderground.com/cat6/Which-Kills-More-People-Extreme-Heat-or-Extreme-Cold>.

<sup>7</sup> Tarik Benmarhnia et al., “Deaths Attributable to Heat and Cold: Comparison of Data Sources and Evaluation of Inconsistencies,” *GeoHealth* 8, no. 3 (March 2024): e2023GH000799, <https://doi.org/10.1029/2023GH000799>.

<sup>8</sup> B. O'Neill et al., “Key Risks Across Sectors and Regions,” in *Climate Change 2022: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Geneva, CH: Intergovernmental Panel on Climate Change, 2021), 2411–2538.

conditioning, and behavioral changes. These factors, which determine the susceptibility of the population to heat, have predominated over the influence of temperature change.”

A 2011 study of 40 major US cities between 1975 and 2004, found that heat wave mortality had decreased, in spite of rising temperatures, due to adaptation.<sup>9</sup>

By reducing mortality from cold events and adapting to heat extremes, rising temperatures are associated with a net saving of lives.

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<sup>9</sup> Keith T. Ingram, Carolyn W. Furman, and John W. Jones, “Climate Change Impact and Adaptation Assessment: A Guide for Coastal Resources Managers,” *Weather, Climate, and Society* 3, no. 4 (October 2011): 234–249, <https://doi.org/10.1175/WCAS-D-11-00055.1>.

## 4 Climate Sensitivity to CO<sub>2</sub> Emissions

Atmospheric CO<sub>2</sub> concentration has increased from its pre-industrial level of 280 parts per million (ppm) to around 425 ppm in 2021.<sup>26</sup> Human-caused warming depends not only on the amount of increasing greenhouse gases, but also on how sensitive the climate is to this increase.

Equilibrium Climate Sensitivity (ECS) is defined as the global surface warming that occurs when the concentration of CO<sub>2</sub> in the atmosphere is doubled, relative to pre-industrial levels.<sup>27</sup> The magnitude of the sensitivity of Earth's climate to increasing concentrations of CO<sub>2</sub> is at the heart of the scientific debate on anthropogenic climate change, and also the public debate on the appropriate policy response to increasing CO<sub>2</sub> in the atmosphere.

The magnitude of the Equilibrium Climate Sensitivity is associated with substantial uncertainties, which are highly consequential for policy making. If climate sensitivity to CO<sub>2</sub> concentration is low, then the impacts of increased emissions are expected to be relatively benign, and the benefits of emissions reductions much reduced. If the sensitivity is high, then even moderate increases of CO<sub>2</sub> could produce significant impacts. Climate sensitivity and estimates of its uncertainty are key inputs into the economic models that drive cost-benefit analyses and estimates of the social cost of carbon.

Since the 1979 Charney Report,<sup>28</sup> estimates in international assessment reports have put ECS between 1.5 and 4.5°C of warming for a doubling of CO<sub>2</sub> relative to pre-industrial levels. The ECS range between 1.5 and 4.5°C is characterized by the IPCC AR5 as the *likely* range (66 percent probability); the AR5 stated that ECS is *extremely unlikely* (95 percent probability) to be below 1.0°C and *very unlikely* (90 percent probability) to exceed 6.5°C.<sup>29</sup>

This range of ECS values has remained stubbornly wide, despite many individual studies claiming to narrow it. Most recently, the IPCC AR6 narrowed the *likely* range of ECS to 2.5–4.0°C and the *very likely* range to be between 2.0 and 5.0°C.<sup>30</sup> This narrowing of the range on the low end is disputed.<sup>31</sup>

Understanding of the uncertainties is illuminated by examining the different methods of estimating climate sensitivity and the confounding effects of feedback processes.

### 4.1 Different Ways of Estimating Equilibrium Climate Sensitivity

Climate scientists use multiple lines of evidence to determine the Equilibrium Climate Sensitivity:

- Climate model simulations
- Historical observations
- Paleoclimatic observations
- Process understanding of feedbacks

By itself, the equilibrium warming effect of a doubling of atmospheric CO<sub>2</sub> is

slightly more than 1°C.<sup>33</sup> The large values of ECS arise from positive feedbacks that amplify the warming effect of CO<sub>2</sub>. Water vapor feedback is positive: a warmer atmosphere may have more water vapor, which itself is a powerful greenhouse gas. Water vapor feedback is partially canceled by the fact that atmospheric temperature decreases more slowly with height above the Earth's surface when atmospheric water vapor increases. Warmer temperatures also result in less snow and sea ice cover, allowing the Earth to absorb more of the sun's radiation. Some simple estimates of these three feedbacks increase the ECS to around 2°C.<sup>34</sup>

Higher values of ECS arise primarily from positive cloud feedbacks. The magnitude, and even the sign, of cloud feedbacks is the greatest source of uncertainty. Elements of cloud feedback include changes in the latitudinal distribution of clouds, changes in the distribution of cloud height (changes in low versus high clouds), changes to the phase of clouds (ice versus liquid), changes in cloud particle size (associated with changes in concentration and/or composition of aerosol particles), changes in the precipitation efficiency of clouds, and even changes in how clouds are distributed over the daily solar cycle.<sup>35</sup> It is difficult for climate models to simulate any of these cloud processes correctly owing to their small scale, let alone predict how they will change in the future. Further, cloud processes modulate the magnitudes of the water vapor, lapse rate, and the surface albedo feedbacks.<sup>36</sup>

#### *4.2.1 Climate model estimates of ECS*

ECS can be determined from climate model simulations by doubling the concentration of CO<sub>2</sub>, allowing several centuries for the warming to equilibrate. To avoid the necessity of long simulations, effective climate sensitivity is commonly evaluated from a 150-year simulation in response to a sudden quadrupling of CO<sub>2</sub>. The spread of ECS values from the CMIP5 climate models (used in the AR5) was 2.0–4.7°C; the spread has increased for the CMIP6 models (used in the AR6) to between 1.8 and 5.7°C.<sup>37,38</sup> Far from the science being settled in relation to the response of the climate system to increasing greenhouse gas concentrations, insofar as it is represented by climate models, uncertainties appear to be growing. The main cause of the overall upward shift in ECS in CMIP6 relative to CMIP5 is a larger positive cloud feedback, driven by changes to the cloud parameterizations in many CMIP6 models.<sup>39</sup>

Climate sensitivity represents an emergent property of climate models—that is, it is not directly parameterized or tuned. However, collections of parameterizations are often chosen to produce an expected value of climate sensitivity, particularly with regards to sub-grid-scale cloud processes. Otherwise plausible models and parameter selections have been discarded because of perceived conflict with this warming rate, or aversion to a model's climate sensitivity being outside an accepted range. For example, Mauritsen and Roeckner (2020) [NEED REF](#) state the following regarding their Max Planck Institute climate model, “We have documented how we tuned the MPI-ESM1.2

global climate model to match the instrumental record of warming; an endeavor which has clearly been successful. Due to the historical order of events, the choice was to do this practically by *targeting an ECS of about 3 K using cloud feedbacks*, [emphasis added] as opposed to tuning the aerosol forcing.” In other words, the modelers chose an ECS value of 3°C and then tuned the cloud parameterizations to match their intended result.

The IPCC AR4 (2007) relied almost exclusively on climate models in its assessment of ECS. The IPCC AR5 (2013) relied on both climate model determinations and determinations from the historical record, noting substantial disagreements between these two methods. Because of concerns about model tuning and the high sensitivity to cloud parameterizations, the IPCC AR6 (2021) did not rely on climate model simulations in their assessment of climate sensitivity, relying on the other three methods in its assessment.

#### 4.2.2 Data-driven estimates of ECS

Climate sensitivity is also estimated from instrumental records of surface temperatures and ocean heat content, combined with estimates of how climate forcings (e.g., greenhouse gases, solar, volcanoes, aerosols) have changed in the past.<sup>40</sup> Using this information, an energy budget method is used to deduce the ECS.

The accuracy of the data-driven methods depends on the quality of the input data. Assumptions are needed about ocean heat storage, and the ocean data is inadequate. The greatest source of uncertainty is the amount and composition of aerosol particles and their interactions with cloud radiative properties (the so-called aerosol indirect effect).

Since 2012 many studies have appeared in the literature tackling these various uncertainties. A recurring theme is that ECS estimates based on historical data turn out to be smaller than ECS estimates inferred from climate models (Sherwood and Forest 2024).

Paleoclimate proxies are used to evaluate the sensitivity of past climates, by comparing paleoclimate changes in the Earth’s temperatures to estimates of changes in forcings. The two most informative periods are the last glacial maximum (around 20,000 years ago), which was about 3–7°C colder than today, and a mid-Pliocene period (roughly three million years ago), which was 1–3°C warmer than today.<sup>41</sup> The limits on cooling during the last glacial maximum give the best single evidence that high values of climate sensitivity are unlikely. However, paleoclimate estimates are associated with very large uncertainties in the estimated temperatures and forcings. Further, estimates of climate sensitivity based on past climate states may not be representative of the current state of the climate system.

Based on a review article by Sherwood et al.(2020), the IPCC AR6 determined the range of ECS values by integrating the historical, paleoclimate and feedback approaches using a Bayesian analysis method.<sup>42</sup> The IPCC AR6 narrowed the likely range of ECS to 2.5–4.0°C.<sup>43</sup> Subsequent to publication of the AR6, Lewis (2023) published an extensive critique of the methodology used in the Sherwood et al. paper to determine the ECS.<sup>44</sup> Key concerns raised by Lewis include errors, outdated input values, and objective versus subjective Bayesian priors in the analysis. Lewis’ analysis found that climate sensitivity is estimated to be much lower and better constrained than in the Sherwood et al. analysis – median 2.16°C (1.75–2.7°C in the 17–83 percent *likely* range), and 1.55–3.2°C in the 5–95 percent *very likely* range. Lewis’ analysis implies that climate sensitivity is considerably more likely to be below 2°C than above 2.5°C.<sup>45</sup> The IPCC AR6 estimated only a 5 percent probability that ECS was below 2.3°C, whereas Lewis (2022) estimated it to be over 50 percent. The most recent publications on the debate between Sherwood et al. and Lewis further defend their respective positions: Sherwood and Foster (2024) and Lewis (2025).

A recent argument, one which the IPCC AR6 emphasized, is that data-driven ECS estimates might understate the future warming response to GHGs based on a so-called “pattern effect” (Forster et al 2021). The tropical Pacific is believed to be highly influential on the overall efficiency with which the Earth’s climate radiates heat to space, but heat in some parts is more efficiently removed than from others. If there is a weakening of the west-to-east temperature gradient in the tropical Pacific, the result would be a concentration of warming in a region where heat is less efficiently removed, raising the ECS of the Earth’s climate system. Most climate models simulate that rising GHGs will weaken the east-west temperature gradient, which led the IPCC in the AR6 to conclude that data-driven ECS estimates understated the *future* ECS value.

However Seager et al. (2019) pointed out that, contrary to models, the east-west temperature gradient has been strengthening rather than weakening over time. They further argued that the mechanism predicting otherwise in climate models was based on a faulty characterization of oceanic dynamics and there is no reason to expect the gradient to weaken. A similar argument was recently made by Lee et al. (2024), who concluded that “the trajectory of the observed trend reflects the response to increasing GHG loading in the atmosphere;” in other words GHG warming should lead to a future strengthening rather than a weakening of the temperature gradient. This implies, if anything, that future ECS in a warming climate will be lower than at present.

#### **4.2 Transient Climate Response**

The Transient Climate Response (TCR) is of greater utility in providing an observational constraint on climate sensitivity. TCR is the amount of warming that would occur at the time when CO<sub>2</sub> doubles, having increased gradually by 1 percent each year over a period of 70 years. Relative to the ECS, observationally- determined



values of TCR avoid the problems of uncertainties in ocean heat uptake and the fuzzy boundary in defining equilibrium arising from a range of timescales for the longer-term feedback processes (e.g., ice sheets). TCR is more generally related to peak warming and better constrained by historical warming, than ECS. The IPCC AR6 judged the *very likely* range of TCR to be 1.2–2.4°C.<sup>47</sup> In contrast to ECS, the upper bound of the TCR is more tightly constrained. For comparison, the TCR values determined by Lewis (2023) is 1.25 to 2.0°C; showing much better agreement with the AR6 values than was seen in a comparison of the ECS values.

A related but more flexible parameter is the Transient Response to cumulative carbon Emissions, or TCRE, which relates global temperature change to the cumulative emissions. TCRE is based upon a linear relationship between global average temperature and cumulative emissions, which holds for cumulative emissions of up to 2 teratons of carbon. For a given value of TCRE, we can calculate the amount of warming expected over a future period in response to scenarios of cumulative carbon emission. The IPCC AR6 provides a *very likely* range for TCRE of 1.0–2.3°C, with a median value of 1.6°C.<sup>48</sup>

#### 4.3. Summary

In the past 5 years, there is a growing realization that climate models are not fit for the purpose of determining the sensitivity of the climate to increasing CO<sub>2</sub> (ECS), owing to the dependence of this sensitivity on poorly resolved processes related to clouds and water vapor.

Data-driven approaches using historical data and paleoclimate reconstructions are generally regarded as more reliable for determining ECS, but their reliability is diminished by data inadequacies.

The IPCC AR6 upper bound for the *likely* range of ECS is 4.0°C, lower than the AR5 value of 4.5°C. This lowering of the upper bound seems well justified by the paleoclimatic estimates of the ECS.

The IPCC AR6 lower bound for the *likely* range of ECS is 2.5°C, substantially higher than the AR5 value of 1.5°C. This raising of the lower bound of the *likely* range of ECS has received a substantial challenge from the analysis of Lewis (2022, 2025) that finds the lower bound of the likely range to be 1.75°C with a median value of 2.16°C.

Estimates of the transient climate response (TCR; TCRE) are more tightly constrained on the upper bound than the ECS.

It is our assessment that a *likely* range for ECS of 1.75 to 4.0°C has the best justification.

SEE FOOTNOTES IN CH 7 of BOOK MANY OF THESE BELOW ARENT  
USED AND CAN BE DELETED

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**From:** Roy Spencer <roywspencer@hotmail.com>  
**Sent:** Thursday, May 1, 2025 12:49 PM  
**To:** Ross McKittrick; Travis Fisher; John Christy; Steven Koonin; Judith Curry  
**Subject:** RE: May 1 status update

This kind of outline update is VERY helpful. I'll touch base with John and do something on U.S. vehicle emissions.

Sent from my Verizon, Samsung Galaxy smartphone

----- Original message -----

From: Ross McKittrick <ross.mckittrick@gmail.com>  
Date: 5/1/25 11:31 AM (GMT-06:00)  
To: Travis Fisher <travis.scott.fisher@gmail.com>, "Roy W. Spencer" <roywspencer@hotmail.com>, John Christy <climateman60@gmail.com>, Steven Koonin <steven.koonin@googlemail.com>, Judith Curry <curry.judith@gmail.com>  
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Also the document would benefit from a glossary of technical terms, acronyms etc. Roy could you make a start on that?

Cheers,  
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**From:** Steven Koonin <steven.koonin@gmail.com>  
**Sent:** Thursday, May 1, 2025 12:40 PM  
**To:** 'Ross McKittrick'; 'Travis Fisher'; 'Roy W. Spencer'; 'John Christy'; 'Steven Koonin'; 'Judith Curry'  
**Subject:** RE: May 1 status update

I have now partially turned to task and will be at full strength Saturday onward.

My intention is to sequentially go through the drafts, editing language and, most importantly, reading with “evil eyes”.

SEK

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**Sent:** Thursday, May 1, 2025 12:31 PM  
**To:** Travis Fisher <travis.scott.fisher@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; John Christy <climateman60@gmail.com>; Steven Koonin <steven.koonin@googlegmail.com>; Judith Curry <curry.judith@gmail.com>  
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**Sent:** Thursday, May 1, 2025 12:31 PM  
**To:** Travis Fisher; Roy W. Spencer; John Christy; Steven Koonin; Judith Curry  
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**Sent:** Friday, May 2, 2025 3:55 PM  
**To:** Ross McKittrick  
**Cc:** Roy Spencer; Steven Koonin; Travis Fisher; John Christy  
**Subject:** Re: my suggested edits of 4

agree that acrim gap works better in ch 4

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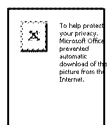
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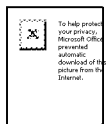
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**Subject:** my suggested edits of 4

See attached. Now on to 5!

SEK



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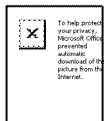
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-Roy

---

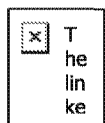
**From:** Steven Koonin  
**Sent:** Friday, May 2, 2025 12:53 PM  
**To:** 'Judith Curry'; 'Roy Spencer'  
**Cc:** 'Ross McKittrick'; 'Travis Fisher'; 'John Christy'  
**Subject:** my suggested edits of 4

See attached. Now on to 5!

SEK

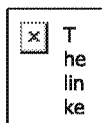
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## 6.1 Introduction

Detection and attribution is concerned with assessing the causal relationship between one or more drivers and a responding system. The Intergovernmental Panel on Climate Change (IPCC) provides clear definitions for detection and attribution in climate science, based on their Sixth Assessment Report (AR6). These terms are crucial for understanding climate change impacts and are used to assess whether observed changes are significant and what caused them. As defined by the IPCC AR6 WGI Glossary:

*Detection:* "Detection of change is defined as the process of demonstrating that climate or a system affected by climate has changed in some defined statistical sense, without providing a reason for that change. An identified change is detected in observations if its likelihood of occurrence by chance due to internal variability alone is determined to be small, for example, <10%."

*Attribution:* "Attribution is defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with a formal assessment of confidence."

The definition of detection emphasizes a statistical approach, focusing on whether changes are significant enough to stand out from natural variability without yet attributing causes.

The attribution process involves assessing how much human activities, such as industrial emissions, versus natural factors, like volcanic eruptions, contribute to observed changes, with a structured confidence level to reflect scientific certainty. Attribution requires the evaluation of the contributions of all external drivers to the system change.

While the IPCC's definitions are clear, there is ongoing scientific debate around attribution methods, particularly in attributing extreme weather events to climate change. The IPCC has long cautioned that methods to establish causality in climate science are inherently uncertain and ultimately depend on expert judgement. The Fourth Assessment Report (Hegerl et al. 2007 p. 668) explained it as follows:

‘Attribution’ of causes of climate change is the process of establishing the most likely causes for the detected change with some defined level of confidence... unequivocal attribution would require controlled experimentation with the climate system. Since that is not possible, in practice attribution of anthropogenic climate change is understood to mean demonstration that a detected change is ‘consistent with the estimated responses to the given combination of anthropogenic and natural forcing’ and ‘not consistent with alternative, physically plausible explanations of recent climate change that exclude important elements of the given combination of forcings’ (IPCC, 2001)... The approaches used in detection and attribution research described above cannot fully account for all uncertainties, and thus ultimately expert judgement is required to give a calibrated assessment of whether a specific cause is responsible for a given climate change.

The Fifth Assessment Report makes the following statement: (Cramer et al. 2014):

“Two broad challenges to the detection and attribution of climate change impacts relate to observations and process understanding. On the observational side, high-quality, long-term data relating to natural and human systems and the multiple factors affecting them are rare. In addition, the detection and attribution of climate change impacts requires an understanding of the processes by which climate change, in conjunction with other factors, may affect the system in question.”

Cramer, W., G.W. Yohe, M. Auffhammer, C. Huggel, U. Molau, M.A.F. da Silva Dias, A. Solow, D.A. Stone, and L. Tibig, 2014: Detection and attribution of observed impacts. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change pp. 979-1037

Because of the complexity of the causal chains in the climate system, investigation of these relationships is exceptionally challenging.

## ***6.2 Attribution methods***

The Intergovernmental Panel on Climate Change (IPCC) employs several attribution methods to assess the causes of observed climate changes, distinguishing between natural and human-induced factors. Below is a concise description of the key attribution methods used by the IPCC:

Optimal Fingerprinting uses statistical techniques to compare observed climate data with climate model simulations of the responses to individual forcings (e.g., anthropogenic greenhouse gases, aerosols, natural forcings like solar variability). A regression model estimates the contribution of each forcing to observed changes, accounting for natural variability and model uncertainties.

Pattern Correlation Methods analyze spatial or temporal patterns of climate variables (e.g. temperature or precipitation) to identify similarities between observed changes and model-simulated responses to specific forcings. This method is useful for attributing shifts in atmospheric circulation or sea surface temperature patterns.

Time Series Analysis examines temporal changes in climate variables to attribute trends to specific forcings. This approach compares long-term observed trends to model simulations with and without anthropogenic forcings. This method helps distinguish between short-term natural variability (e.g., El Nino) and long-term anthropogenic signals.

Multi-Step Attribution connects changes to impacts and then to forcings. An example is linking greenhouse gas emissions to warming, warming to increased heatwaves, and heatwaves to specific societal impacts.

Process-Based Attribution focuses on understanding the physical mechanisms behind observed changes. This approach combines observations, climate models, and theoretical understanding to attribute changes in specific processes to forcings. This approach is often used for regional climate phenomena, such as monsoon changes or polar amplification

Multi-Model and Ensemble Approaches use multiple climate models (e.g. CMIP6 ensemble) to account for uncertainties and improve confidence in attribution results. Large ensembles of simulations help separate the forced climate signal from internal variability.

Extreme Event Attribution assesses the role of human influence in the likelihood of occurrence or intensity of extreme weather events (e.g. heat waves, droughts). Methods include:

- Fraction of Attributable Risk quantifies how much anthropogenic climate change has altered the probability of an event
- Probabilistic Event Attribution uses large ensembles of climate model simulations to compare event likelihood in a world with and without human influence
- Storyline Approach examines the physical processes driving an event and evaluates how anthropogenic forcings modified those processes

### 6.3 Attribution of global warming

Attribution statements of global warming in the three most recent IPCC Assessment reports are:

AR4: “Most of the observed increase in global average temperatures since the mid-20<sup>th</sup> century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations.”

AR5: “It is *extremely likely* that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together. The best estimate of the human- induced contribution to warming is similar to the observed warming over this period.”

AR6: “The *likely* range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019 is 0.8°C to 1.3°C, with a best estimate of 1.07°C. It is *likely* that well-mixed GHGs contributed a warming of 1.0°C to 2.0°C, other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C, natural drivers changed global surface temperature by –0.1°C to +0.1°C, and internal variability changed it by –0.2°C to +0.2°C. It is *very likely* that well-mixed GHGs were the main driver of tropospheric warming since 1979.”

The AR4 and AR5 attribution statements reference the warming to the mid-20<sup>th</sup> century, the period when greenhouse gas emissions began rapidly increasing. The words “most” and “more than half” are deliberately imprecise, potentially ranging from 51 to 99% of the warming – presumably this imprecision is to account for potential structural uncertainties such as natural internal variability. The confidence level increases from *very likely* to *extremely likely* from AR4 to AR5. The structure of the attribution statement in the AR6 is fundamentally different, referencing the warming to the period 1850-1900. The AR6 attribution statement is more precise numerically, but with a lower level of confidence at “likely” – the AR6 attributes essentially all of the warming to increases in greenhouse gases. The most confident statement from the AR6 relates to the tropospheric warming since 1979, using the words “main driver” and “*very likely*.”

There are two areas of substantive criticism of the IPCC assessment of the causes of the recent warming: inadequate assessment of natural climate variability, and inappropriate statistical methods. Both of these issues are relevant not only in context of the main policy-relevant statement of the IPCC concerning attribution of the recent warming, but also because the global warming attribution provides the basis for extreme event attribution

#### 6.3.1 Natural climate variability

The IPCC AR6 states that natural external drivers since 1850-1900 have changed global surface temperature by –0.1°C to +0.1°C, and internal variability has changed it by –0.2°C to +0.2°C – on average, having essentially no net impact on the warming since 1850-1900. This assessment of the contributions of natural variability has been disputed by a number of publications that question the magnitudes of the contributions from solar forcing and internal variability from the large-scale ocean circulations.

If the Equilibrium Climate Sensitivity to CO<sub>2</sub> is low (REF PREVIOUS CHAPTER), then natural climate variability becomes more important in the attribution of the recent warming. Further, if natural variability is higher, then estimates of the Equilibrium Climate Sensitivity from the historical period would be lower (Scafetta, 2023).



Connolly, R.; Soon, W.; Connolly, M.; Baliunas, S.; Berglund, J.; Butler, C.J.; Cionco, R.G.; Elias, A.G.; Fedorov, V.M.; Harde, H.; et al. How Much Has the Sun Influenced Northern Hemisphere Temperature Trends? An Ongoing Debate. *Res. Astron. Astrophys.* 2021, 21, 131.

Soon, W.; Connolly, R.; Connolly, M.; Akasofu, S.-I.; Baliunas, S.; Berglund, J.; Bianchini, A.; Briggs, W.M.; Butler, C.J.; Cionco, R.G.; et al. The Detection and Attribution of Northern Hemisphere Land Surface Warming (1850–2018) in Terms of Human and Natural Factors: Challenges of Inadequate Data. *Climate* 2023, 11, 179. <https://doi.org/10.3390/cli11090179>

Scafetta, N (2023) Empirical assessment of the role of the Sun in climate change using balanced multi-proxy records. *Geoscience Frontiers*,

### *Solar variability*

The IPCC AR5 concluded that the best estimate of radiative forcing due to Total Solar Irradiance (TSI) changes for the period 1750–2011 was  $0.05 \text{ W/m}^2$ . The IPCC AR6 acknowledges a much larger range of estimates of changes in TSI over the last several centuries, stating that the TSI between the Maunder Minimum (1645–1715) and the second half of the twentieth century increased by  $0.7\text{--}2.7 \text{ W/m}^2$ , a range that includes both low and high variability TSI data sets.<sup>41</sup> However, the recommended forcing dataset for the CMIP6 climate model simulations used in the AR6 for attribution studies averages two data sets with low solar variability.<sup>42</sup> (FOOTNOTE REFS FROM CH 8 of book)

While the IPCC AR6 shows a substantially greater solar impact than does the AR5, the overall impact on the climate was assessed to be small compared to anthropogenic forcing of climate change. However, the impact of solar variations on the climate is uncertain and subject to substantial debate CLIMATE DIALOG REF FROM BOOK - something that you would not infer from the IPCC assessment reports.

Exactly how TSI has changed over time has been a challenging problem to resolve. Since 1978, there have been direct measurements of TSI from satellites. However, the data exhibit non-negligible inconsistencies, and interpreting any multi-decadal trends in TSI requires comparisons of observations from overlapping satellites. Substantial uncertainty exists in the TSI composites, particularly owing to a gap in coverage during 1989 to 1992 that prevented direct cross-calibrations between two successive satellites. This rather arcane issue of cross-calibration of two satellite records has profound implications. There are a number of rival composite TSI datasets, disagreeing as to whether TSI increased or decreased during the period 1986–96. Further, the satellite record of TSI is used for calibrating proxy models, whereby past solar variations are inferred from sunspots and cosmogenic isotope measurements.<sup>37</sup>

There is substantial evidence for high solar activity in the second half of the 20<sup>th</sup> century (starting in 1959) and extending into the 1990's, before a decline in the early 21<sup>st</sup> century; this period is often termed the “Modern Maximum.”

Chatzistergos et al. 2023, Solanki et al. 2004, Usoskin et al. 2007

However, some scientists have concluded that it is not possible to be confident of any multi-decadal trend in TSI (Schmutz, 2021).

As a result of this uncertainty, some reconstructions for past values of TSI (since 1750) have low variability, implying a very low impact of solar variations on global mean surface temperature, whereas datasets with high TSI variability can explain more than 70% percent of the temperature

variability since preindustrial times (Soon et al., 2023, Connolly et al, 2021). Hence, the choice of which TSI satellite record used in an analysis can substantially influence how much climate change is attributed to human versus natural forcings.

Chatzistergos, T., et al. (2023). Long-term changes in solar activity and irradiance. *Journal of Atmospheric and Solar-Terrestrial Physics*. [Link](#)

Connolly, R., et al. (2021). How much has the Sun influenced Northern Hemisphere temperature trends? An ongoing debate. *arXiv*. [Link](#)

Connolly et al., “Challenges in the Detection and Attribution of Northern Hemisphere Surface Temperature Trends Since 1850.”

A review article on this topic was recently published in the journal *Research in Astronomy and Astrophysics* (Connolly et al., 2023). The article had 23 co-authors with a range of perspectives, but who were united by their agreement not to take the consensus approach of the IPCC. Rather, the paper emphasized where dissenting scientific opinions exist as well as identifying areas where there is scientific agreement. The authors found that the Sun/climate debate is an issue where the IPCC’s consensus statements were prematurely achieved through the suppression of dissenting scientific opinions.

There is growing evidence that other aspects of solar variability, which are referred to as solar indirect effects, amplify TSI forcing or are independent of TSI forcing. Scafetta et al. (2023) suggests that ~80% of solar influence on climate may stem from non-TSI mechanisms. Candidate processes include: solar ultraviolet changes; energetic particle precipitation; atmospheric-electric-field effect on cloud cover; cloud changes produced by solar-modulated galactic cosmic rays; large relative changes in the magnetic field; and the strength of the solar wind. Solar indirect effects are not included in climate models, although indirect methods of estimating these effects suggest significant influence. However, claims of non-TSI mechanisms influencing climate are uncertain and debated.

□ Scafetta, N., et al. (2023). Empirical assessment of the role of the Sun in climate change using balanced multi-proxy solar records. *Geoscience Frontiers*. [Link](#)

#### *Natural variability of large-scale ocean circulations*

Variations in global mean surface temperature are linked to recurrent large-scale variations in ocean circulation patterns. These circulation patterns include the Atlantic Multidecadal Oscillation (AMO), the Pacific Decadal Oscillation (PDO) and the El Nino-Southern Oscillation (ENSO). These circulation patterns influence ocean heat uptake and heat distribution, and also influence atmospheric circulation patterns and cloud distributions. There is some debate as to whether these variations are strictly internal to the climate system, or whether this variability can have a solar/astronomical origin or can be influenced by large volcanic eruptions.

While climate models simulate the large-scale ocean circulations and internal climate variability, the simulated magnitude in the multi-decadal band is too low in most models relative to observations, and the phasing of the variability in long-term climate simulations is not synced with the actual, observed climate variations. Averaging multiple simulations from climate models effectively averages out the internal variations, leaving only the forced climate variability (e.g., CO<sub>2</sub> forcing). With most of the modern warming beginning in the late 1970’s, the recent 50-year warming is on the same time scale as

the multi-decadal oscillations of the AMO and PDO.

Here are summary statements from the IPCC AR5 and AR6 reports:

"Decadal variability in the Pacific, associated with the PDO or IPO, contributes significantly to regional and global temperature trends, but the relative contributions of internal variability and external forcing are difficult to disentangle in CMIP5 simulations." (AR5 Chapter 10, Section 10.3.1, p. 10- 28)

"Since AR5, there has been increased understanding of the role of internal variability, such as ENSO, PDO, and AMO, in modulating regional climate trends. However, limitations in simulating the exact timing and amplitude of these modes in CMIP6 models contribute to uncertainties in attributing observed changes to anthropogenic forcing (high confidence)." (AR6 Chapter 3, Section 3.7, p. 3-115)

The amplitude of the peak-to-trough impact of the multi-decadal oscillations on global temperatures has been assessed by the IPCC AR6: "The likely range of change due to internal variability is  $-0.2^{\circ}\text{C}$  to  $+0.2^{\circ}\text{C}$ ." This implies a trough-to-peak change of  $0.4^{\circ}\text{C}$ . Over many centuries, any global temperature changes from the troughs and peaks will cancel out, with little to no net impact.

However, with a nominal timescale of 60-80 years for oscillations such as the AMO and PDO, the timing of the peaks and troughs can be confused with the secular trend. This becomes very relevant for attributing the warming for the 50 years since 1975, during which most of the warming has occurred. Even if climate models have the correct amplitude of the multidecadal oscillations, the timing of the peaks and troughs is not adequately simulated, with each model and individual ensemble simulating a different phasing. Once the simulations of the ensemble members and different models are averaged, the natural internal variability contribution is averaged out, effectively cancelling the role of natural internal variability in the attribution process.

The Great Pacific Climate Shift of 1976-1977 was a notable climatic event characterized by an abrupt change in the North Pacific Ocean's atmosphere-ocean system that interacted with global climate patterns. This shift is closely associated with the Pacific Decadal Oscillation (PDO) that oscillates between warm and cool phases over decades. The 1976 shift marked a transition from a predominantly negative (cool) PDO phase (1947–1976) to a positive (warm) phase (1977 through 2000), with significant implications for global and regional climate patterns including the frequencies of El Nino and La Nina events. The Great Pacific Climate Shift coincided with the beginning of a period of accelerated global warming (REF TO A FIG OF GLOBAL TEMP ANOMALIES ELSEWHERE IN DOC) When the Great Pacific Climate Shift is accounted for in climate attribution analyses since 1950, it has been found that 40 percent or more of the warming in the second half of the 20<sup>th</sup> century was caused by natural internal variability (McLean et al, 2009; Tung and Zhou, 2013; Chylek et al., 2016; Scafetta, 2021).

McLean et al. (2009) "Influence of the Southern Oscillation on tropospheric temperature," J. Geophys. Res., 114

Ka-Kit Tung and Jiansong Zhou, "Using Data to Attribute Episodes of Warming and Cooling in Instrumental Records," Proceedings of the National Academy of Sciences 110, no. 6 ( January 23, 2013): 2058–2063, <https://doi.org/10.1073/pnas.1212471110> .

Petr Chylek et al., “The Role of Atlantic Multi-Decadal Oscillation in the Global Mean Temperature Variability,” *Climate Dynamics* 47, no. 9–10 (February 20, 2016): pp. 3271–3279, <https://doi.org/10.1007/s00382-016-3025-7>.

Scafetta, N. Reconstruction of the Interannual to Millennial Scale Patterns of the Global Surface Temperature. *Atmosphere* 2021, 12, 147. <https://doi.org/10.3390/atmos12020147>

### 6.3.2 *Statistical methods*

Optimal fingerprinting is a statistical technique that compares observed climate data with climate model simulations to identify patterns (or "fingerprints") associated with human influence. Optimal fingerprinting has been heavily used in the climate literature for establishing attribution; studies applying it have been cited thousands of times, and it has been prominently featured by the IPCC since the Third Assessment Report in 2001.

A series of papers by McKittrick (McKittrick, 2022; McKittrick et al., 2023; McKittrick, 2024) has challenged the statistical methods commonly used in optimal fingerprinting and broader attribution analyses, based on commonly adopted practices in econometrics. These critiques highlight potential biases that could lead to over- or under-estimation of human influence on climate, and problems with the method that reduce confidence in the analysis results.

McKittrick (2022) challenged the methodology introduced by Allen and Tett (1999) for climate change attribution, which is a cornerstone of optimal fingerprinting. McKittrick argues that this methodology violates key conditions of the Gauss-Markov theorem, particularly the requirement that the conditional expectation of errors must be zero. This violation leads to biased and inconsistent estimates of attribution, undermining the reliability of the method.

McKittrick et al. (2023) addresses a paradox in climate attribution studies: standard trend models assume stationary (mean-reverting) error terms, while the climate econometrics literature suggests that if anthropogenic forcing is dominant, temperature trends should exhibit nonstationary (unit root) error terms, which could serve as a "fingerprint" for human influence. McKittrick and co-authors use tools from time series econometrics to resolve this issue, formalizing a hypothesis that temperature series contain both a nonstationary forcing component (due to anthropogenic influences) and a stationary "weather noise" component. This combination can bias unit root tests toward over-rejection, leading to misinterpretations in attribution studies.

McKittrick (2024) addresses the concern that for more than 20 years climate scientists—virtually alone among scientific disciplines—have used Total Least Squares (TLS) to estimate anthropogenic greenhouse gas signal coefficients, despite its tendency to be unreliable unless some strong assumptions hold that in practice are unlikely to be true. Under conditions which easily arise in optimal fingerprinting for climate attribution, TLS yields estimates with large positive biases. Thus, any study that has used TLS for optimal fingerprinting without verifying that it is appropriate in the specific data context has likely overstated the result.

While these analyses do not prove that all of the results from using these methods are wrong, it does show that the basis on which they were believed to be correct is non-existent – hence reducing confidence in the results. McKittrick's work underscores the importance of statistical rigor in attributing climate changes and the need to bridge the gap between econometric and climatological approaches.

## 6.4 Extreme event attribution

The IPCC AR6 provides an ambiguous assessment of the role of global warming in the historical record extreme weather and climate events. Chapter 11 of WG1 states:

"Evidence of observed changes in extremes and their attribution to human influence (including greenhouse gas and aerosol emissions and land-use changes) has strengthened since AR5, in particular for extreme precipitation, droughts, tropical cyclones and compound extremes (including dry/hot events and fire weather). Some recent hot extreme events would have been extremely unlikely to occur without human influence on the climate system."

By contrast, Chapter 12 of WG1 (Table 12.12) paints a different picture – presumably, the expert judgment of different groups of authors for the two chapters came to different conclusions:

- High confidence in an increase in extreme heat events in tropical regions where observations allow trend estimation and in most regions in the mid-latitudes, medium confidence elsewhere
- Medium confidence in a decrease in extreme cold events in Australia, Africa and most of northern South America where observations allow trend estimation
- No evidence of emergence in the historical period of a change in river floods, heavy precipitation, drought, fire weather, severe wind storms, and tropical cyclones

While the overall issue of detecting changes in extreme weather events and their attribution remains ambiguous, most of the activity in this area relates to the attribution of single extreme weather events. The most prominent effort is the World Weather Attribution (WWA) [WEB LINK](#), which is an international research initiative that focuses on extreme event attribution, analyzing how climate change influences the likelihood and intensity of extreme weather events. The approach used by the WWA runs large ensembles of regional climate models to compare the event in today's climate versus a pre-industrial climate without human-caused warming. WWA plays a significant role in linking extreme weather to climate change, using rapid probabilistic attribution to inform public and policy discussions.

However, the WWA's non-peer-reviewed reports, funding ties, and methodological challenges have sparked controversies, with critics questioning the robustness and impartiality of its conclusions. Despite these issues, WWA's work continues to shape climate science and media narratives. Technical criticisms of the approach include: neglect of a formal detection process; an implicit assumption that 100% of the post-industrial warming is caused by CO<sub>2</sub>; and failure to adequately account for natural internal climate variability.

Beyond the issues raised by event attribution approaches, there exist major challenges to the detection step – a step that is commonly skipped, contra to the IPCC's established detection and attribution approach. Extreme events are by definition rare. Many analyses of extreme event types (including the US National Assessment Reports) only evaluate data since 1950 or 1970. However, as emphasized by Chapter xxx, many of the worst extreme weather and climate events in U.S. history occurred in the first half of the 20<sup>th</sup> century and the 19<sup>th</sup> century. And if paleoclimate reconstructions are also considered, it becomes very difficult for an event to pass the detection thresholds of exceeding what is expected from natural variability, particularly if a reasonably sized geographic region is considered.

In spite of these concerns, the U.S. is presently considering something like the WWA, which is being investigated by a NASEM Panel on Attribution of Extreme Weather and Climate Events and their impacts.

<https://www.nationalacademies.org/our-work/attribution-of-extreme-weather-and-climate-events-and-their-impacts>

Extreme weather events can be extreme in terms of the magnitude of individual events, the frequency of events crossing some threshold, or clustering of extreme events. It needs to be acknowledged that extreme events are by definition rare, and short historical records (even century long records) are insufficient for formulating meaningful statistics about return times and event likelihood.

Case studies from two recent high impact extreme events in the U.S. are provided to illustrate the challenges and ambiguities in attributing the frequency and intensity of extreme weather events to human-caused warming.

#### *6.4.1 Case study – 2021 Western North America heat wave*

The 2021 Western North America heat wave was an extreme heat wave that affected much of Western North America in late June 2021. In particular, surface temperature records were set in Portland, OR (115 °F; previous record 107°F) and Seattle, WA (108 °F; previous record 103°F).

The WWA provided the following attribution statements:

<https://www.worldweatherattribution.org/western-north-american-extreme-heat-virtually-impossible-without-human-caused-climate-change/>

<https://www.worldweatherattribution.org/wp-content/uploads/NW-US-extreme-heat-2021-scientific-report-WWA.pdf>

- Based on observations and modeling, the occurrence of this heatwave was virtually impossible without human-caused climate change.
- The event is estimated to be about a 1 in 1000-year event in today's climate.
- The event would have been at least 150 times rarer without human-induced climate change.
- This heatwave was about 2°C hotter than it would have been if it had occurred at the beginning of the industrial revolution (when global mean temperatures were 1.2°C cooler than today).

Mass et al. (2024) summarizes the proximate sequence of compound events leading to the heat wave. There was a record-breaking midtropospheric ridge over the Pacific Northwest, forced by a tropical disturbance in the western Pacific. This produced record-breaking midtropospheric temperatures, strong subsidence in the lower atmosphere, low-level easterly flow that produced downslope warming on regional terrain and the removal of cooler marine air, and an approaching low-level trough that enhanced downslope flow. The event occurred at a time of maximum solar insolation, and drier-than-normal soil moisture. Using a storyline approach, Mass et al. assessed that there is no trend in drought and dry soils in the Pacific Northwest; there is no evidence of global warming producing stronger ridges of high pressure, and no observed trend in heat waves or record temperatures in the region. They concluded that although anthropogenic warming may have contributed as much as 2°F to the magnitude of the event, there is little evidence of further amplification of the event from increasing greenhouse gases.

<https://journals.ametsoc.org/view/journals/wefo/39/2/WAF-D-23-0154.1.xml>

A more sophisticated statistical analysis of a model-based attribution study of this heat wave was conducted by Bercos-Hickey et al. (2022)

<https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2022GL099396> Because this event is a far outlier and far above the bounds of Generalized Extreme Value distributions fitted from historical data, they concluded that estimates of return times, quantitative changes in event magnitude and frequency, and probability of the extreme temperatures such as provided by the WWA are not accurate and are made with low confidence. They found that hindcast attribution methods using an ensemble of regional climate models, combined with Pearl (2009) causal inferences, can provide limited and conditional information about the magnitude of the human influence on this heatwave – they provided a more highly constrained estimate that human activities caused a ~1.4°C–1.8°F increase in the daily maximum temperatures.

The 2021 Western North America heatwave was a rare and unprecedented compound weather event, that broke century-old temperature records by as much as 9°F. While there is little doubt that anthropogenic global warming contributed to the probability and magnitude of the extreme temperatures, the uniqueness of the event challenges quantifying this influence by traditional event attribution methods.

Van Oldenborgh et al. (2022) summarize the challenges of attributing heat waves.

<https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021EF002271>

A warming climate means that a fixed temperature threshold is passed more often, and hence the probability of extreme heat increases. However, land use changes, vegetation change, irrigation, air pollution, and other changes also drive local and regional trends in heatwaves. Sometimes these factors enhance heatwave intensity, but they can also counteract the effects of climate change. Temperature variability is unrealistic in many climate models, and can fail standard quality checks. Therefore, reliable attribution of heatwaves remains a major scientific challenge in many regions, particularly where the moisture budget is not well simulated, and where land surface changes, changes in short-lived forcings, and soil moisture interactions are important.

#### 6.4.2 Case study – Hurricane Harvey rainfall ~~IDONT LOVE THIS EXAMPLE. DELETE? MAYBE SOMETHING ELSE?~~

Hurricane Harvey made landfall in southern Texas on August 24, 2017 as a Category 4 hurricane. The primary damage from Harvey occurred after the storm had been downgraded to a tropical storm and stalled near the coastline with a stationary front along the TX/LA border, dropping torrential and unprecedented amounts of rainfall over Texas. Hurricane Harvey provides an informative example of the challenges of detection for a rare event, and also the complexity of extraneous factors that can influence such an event.

The first issue to consider is detection. Harvey set the record for most amount of rainfall from a continental U.S. landfalling hurricane (60 inches), going back at least to the 1880's when comprehensive records begin (Landsea, 2017). The previous top four rainfall producers for U.S. landfalling hurricanes were: Tropical Storm Amelia (1978) with 48 inches in Texas, Hurricane Easy (1950) with 45 inches in Florida, Tropical Storm Claudette (1979) with 45 inches in Florida, and Tropical Storm Allison (2001) with 40 inches in Texas. Looking more broadly at North American hurricanes that made landfall in Central American and the Caribbean, Roth (2017) identifies the following landfalling hurricanes that produced more rainfall than Harvey: 100 inches in Cuba from Hurricane Flora (1963), 96 inches in Jamaica from the November 1909 Hurricane, 63 inches in Nicaragua from Hurricane Mitch (1998), and 62 inches in Mexico from Hurricane Wilma (2005). Hurricane Harvey's rainfall arguably meets the detection criteria, whereby an attribution analysis is justified, although Harvey's rainfall was far from unprecedented from historic Atlantic hurricane landfalls.

In addressing the attribution of extreme rainfall from a landfalling hurricanes, there are several factors leading to excessive rainfall that aren't associated with temperature. Slow motion of the hurricane near landfall can lead to high amounts of local rainfall (e.g. Wilma – 2005; Harvey – 2017;). Mountains/hills near the coast magnify rainfall potential due to forced upslope flow (e.g. Mitch – 1998). Upper-level troughs and cold fronts can lead to excessive rainfall (e.g. Floyd – 1999). Horizontally large tropical cyclones have larger rain footprints, which can lead to excessive rainfall owing to the longer time frame over which rainfall falls at any one location.

The WWA attribution analysis of Hurricane Harvey's rainfall (Oldenburgh et al., 2017) found that human-caused climate change made the heavy rainfall associated with Hurricane Harvey roughly three times more likely and 15% more intense.

<https://iopscience.iop.org/article/10.1088/1748-9326/aa9ef2#:~:text=This%20would%20indicate%20that%20the,to%20Houston's%20flood%20protectio n%20system.&text=Author%20to%20whom%20any%20correspondence%20should%20be%20addressed>

Several publications based on model simulations have concluded that as much as 40% of the rainfall from Hurricane Harvey was caused by human-caused global warming (Emanuel 2017; Risser and Wehner 2017). The rationale for these assessments was that prior to the beginning of summer of 2017, sea surface temperatures in the western Gulf of Mexico exceeded 86 °F and ocean heat content was the highest on record in the Gulf of Mexico (Trenberth et al. 2017). However, El Niño–Southern Oscillation (ENSO) and Atlantic circulation patterns contributed to this elevated heat content.

Landsea (2017) summarizes the arguments for more rainfall from tropical cyclones traveling over a warmer ocean. Simple thermodynamic calculations suggest that the amount of rainfall in the tropical latitudes would increase by about 4% per °F of sea surface temperature increase. Examining a 300 mile radius circle for nearly all of the rain implies that about 10% more total hurricane rainfall for a warming of 2-2.5 °F. The Gulf of Mexico has warmed about 0.7 °F since 1960. Even if it is assumed that all of this warming is due to manmade global warming suggests that roughly 3% of hurricane rainfall today can be reasonably attributed to manmade global warming. Hence, only about 2 inches of Hurricane Harvey's peak amount of 60 inches can be linked to manmade global warming.

Aryal et al. (2018) examined the contribution of North Atlantic hurricanes to flooding and heavy rainfall across the continental U.S. Their analysis does not point to any significant changes in the magnitude or frequency of floods. They found that the North Atlantic Oscillation (NAO) plays a significant role in hurricane-related extreme rainfall along the U.S. East Coast, while ENSO is most strongly linked to the hurricane-related precipitation in Texas.

With regards to the rainfall associated with landfalling hurricanes, there is no clear signal of increasing rainfall owing to the complexity of the factors contributing to hurricane-induced rainfall.

## **6.5 Summary**

There is an ongoing scientific debate around attribution methods, particularly in attributing extreme weather events to climate change. The IPCC has long cautioned that methods to establish causality in climate science are inherently uncertain and ultimately depend on expert judgement.

There are two areas of substantive criticism of the IPCC assessment of the causes of the recent warming: inadequate assessment of natural climate variability, and inappropriate statistical methods.

Detection of extreme weather events is challenged by their rarity, requiring a long data set and a choice of region and spatial scale to evaluate their occurrence against the background of natural weather and climate variability.

The most robust attribution statements for an extreme event relate to an incremental change (e.g. a temperature change or percent change in rainfall). Statements related to return times, quantitative changes in event magnitude and frequency, and probability of the extremes are not accurate and are made with low confidence. There is no evidence in a change of weather or climate regime patterns from increasing greenhouse gases that would amplify or dampen extreme weather events.



---

**From:** Judith Curry <curry.judith@gmail.com>  
**Sent:** Friday, May 2, 2025 3:18 PM  
**To:** Ross McKittrick  
**Cc:** Roy Spencer; Steven Koonin; Travis Fisher; John Christy  
**Subject:** Re: my suggested edits of 4  
**Attachments:** 6 combined.docx

Ross, in my attribution chapter (attached), the statistical issues you raise are about 20% of the overall issue.

Outline is

Introduction

Attribution methods (others besides optimal fingerprinting

Attribution of global warming

On Fri, May 2, 2025 at 12:12 PM Ross McKittrick <[ross.mckittrick@gmail.com](mailto:ross.mckittrick@gmail.com)> wrote:

There are going to be a few places where topics arguably belong in two or more places, and we may find it hard to settle that until we have something like a complete draft to read through at one sitting. I like having the solar and aerosol discussion here as part of the topic of influences (including natural ones) on the climate. I think the important thing about the attribution chapter is explaining that scientists use statistical methods to infer causation in the absence of experimental evidence and there are problems/limitations with any such methods.

I have no trouble reducing the use of quotes. I tend to over-include them because I think people need to see that the cited sources actually said what is attributed, but lengthy inset quotes slow down the flow. And I'm fine switching the Zacharias quote out (there are even shabbier ones from Lean) and replacing it with the Connolly summary.

To Roy's point: I think we make a start at articulating the importance of natural influences in Part I, but if more needs to be said Roy maybe you could try drafting some text.

Ross

On Fri, May 2, 2025 at 2:53 PM Roy Spencer <[roywspencer@hotmail.com](mailto:roywspencer@hotmail.com)> wrote:

I feel like there is a disconnect that results from the first 2 Parts, and I am willing to be overruled by the majority on this:

Part I: Direct human influence on ecosystems and the climate

Part II: Climate response to greenhouse gas emissions

Part II addresses "attribution", but the reader might well ask, if there are only **human** influences on climate worthy of description in Part I, then why discuss uncertainties over attribution, if you've only told me about humans influencing the climate?

This is why I previously pointed out that radiative forcing of the climate system can be NATURAL as well as anthropogenic. We have papers published, as does Dick Lindzen, and maybe Judith Curry as well, discussing this.

All you have to do is look at the large variability in TOA radiative flux anomalies vs. surface temperature anomalies, and you can see that most of those flux variations are NOT feedback-related (linearly related to temperature), they instead PRECEDE temperature changes and so are the CAUSE of temperature changes (natural radiative forcing). This is natural radiative forcing (because in the forcing-feedback paradigm of climate change, if it's not feedback, it's forcing).

Unless we are willing to challenge the premise that external (TOA) radiative forcing is ONLY due to humans and volcanoes, we lose the chance to point out, up front, that the climate system can cause its own radiative forcing, and thus climate change.

Do we KNOW this has happened on climate time scales? No. But there is an awful lot of evidence of the RWP, MWP, and LIA. What caused them? We really don't know.

But simply assuming (for example) that the average albedo of Earth has been divinely inspired to be a constant 0.300 for ever and ever amen seems rather presumptuous.

Just my 2 cents.

-Roy

---

**From:** Steven Koonin  
**Sent:** Friday, May 2, 2025 12:53 PM  
**To:** 'Judith Curry'; 'Roy Spencer'  
**Cc:** 'Ross McKittrick'; 'Travis Fisher'; 'John Christy'  
**Subject:** my suggested edits of 4

See attached. Now on to 5!

SEK



Judith Curry, President  
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<http://www.cfanclimate.net>

## 6.1 Introduction

Detection and attribution is concerned with assessing the causal relationship between one or more drivers and a responding system. The Intergovernmental Panel on Climate Change (IPCC) provides clear definitions for detection and attribution in climate science, based on their Sixth Assessment Report (AR6). These terms are crucial for understanding climate change impacts and are used to assess whether observed changes are significant and what caused them. As defined by the IPCC AR6 WGI Glossary:

*Detection:* "Detection of change is defined as the process of demonstrating that climate or a system affected by climate has changed in some defined statistical sense, without providing a reason for that change. An identified change is detected in observations if its likelihood of occurrence by chance due to internal variability alone is determined to be small, for example, <10%."

*Attribution:* "Attribution is defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with a formal assessment of confidence."

The definition of detection emphasizes a statistical approach, focusing on whether changes are significant enough to stand out from natural variability without yet attributing causes.

The attribution process involves assessing how much human activities, such as industrial emissions, versus natural factors, like volcanic eruptions, contribute to observed changes, with a structured confidence level to reflect scientific certainty. Attribution requires the evaluation of the contributions of all external drivers to the system change.

While the IPCC's definitions are clear, there is ongoing scientific debate around attribution methods, particularly in attributing extreme weather events to climate change. The IPCC has long cautioned that methods to establish causality in climate science are inherently uncertain and ultimately depend on expert judgement. The Fourth Assessment Report (Hegerl et al. 2007 p. 668) explained it as follows:

‘Attribution’ of causes of climate change is the process of establishing the most likely causes for the detected change with some defined level of confidence... unequivocal attribution would require controlled experimentation with the climate system. Since that is not possible, in practice attribution of anthropogenic climate change is understood to mean demonstration that a detected change is ‘consistent with the estimated responses to the given combination of anthropogenic and natural forcing’ and ‘not consistent with alternative, physically plausible explanations of recent climate change that exclude important elements of the given combination of forcings’ (IPCC, 2001)... The approaches used in detection and attribution research described above cannot fully account for all uncertainties, and thus ultimately expert judgement is required to give a calibrated assessment of whether a specific cause is responsible for a given climate change.

The Fifth Assessment Report makes the following statement: (Cramer et al. 2014):

“Two broad challenges to the detection and attribution of climate change impacts relate to observations and process understanding. On the observational side, high-quality, long-term data relating to natural and human systems and the multiple factors affecting them are rare. In addition, the detection and attribution of climate change impacts requires an understanding of the processes by which climate change, in conjunction with other factors, may affect the system in question.”

Cramer, W., G.W. Yohe, M. Auffhammer, C. Huggel, U. Molau, M.A.F. da Silva Dias, A. Solow, D.A. Stone, and L. Tibig, 2014: Detection and attribution of observed impacts. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change pp. 979-1037

Because of the complexity of the causal chains in the climate system, investigation of these relationships is exceptionally challenging.

## ***6.2 Attribution methods***

The Intergovernmental Panel on Climate Change (IPCC) employs several attribution methods to assess the causes of observed climate changes, distinguishing between natural and human-induced factors. Below is a concise description of the key attribution methods used by the IPCC:

Optimal Fingerprinting uses statistical techniques to compare observed climate data with climate model simulations of the responses to individual forcings (e.g., anthropogenic greenhouse gases, aerosols, natural forcings like solar variability). A regression model estimates the contribution of each forcing to observed changes, accounting for natural variability and model uncertainties.

Pattern Correlation Methods analyze spatial or temporal patterns of climate variables (e.g. temperature or precipitation) to identify similarities between observed changes and model-simulated responses to specific forcings. This method is useful for attributing shifts in atmospheric circulation or sea surface temperature patterns.

Time Series Analysis examines temporal changes in climate variables to attribute trends to specific forcings. This approach compares long-term observed trends to model simulations with and without anthropogenic forcings. This method helps distinguish between short-term natural variability (e.g., El Nino) and long-term anthropogenic signals.

Multi-Step Attribution connects changes to impacts and then to forcings. An example is linking greenhouse gas emissions to warming, warming to increased heatwaves, and heatwaves to specific societal impacts.

Process-Based Attribution focuses on understanding the physical mechanisms behind observed changes. This approach combines observations, climate models, and theoretical understanding to attribute changes in specific processes to forcings. This approach is often used for regional climate phenomena, such as monsoon changes or polar amplification

Multi-Model and Ensemble Approaches use multiple climate models (e.g. CMIP6 ensemble) to account for uncertainties and improve confidence in attribution results. Large ensembles of simulations help separate the forced climate signal from internal variability.

Extreme Event Attribution assesses the role of human influence in the likelihood of occurrence or intensity of extreme weather events (e.g. heat waves, droughts). Methods include:

- Fraction of Attributable Risk quantifies how much anthropogenic climate change has altered the probability of an event
- Probabilistic Event Attribution uses large ensembles of climate model simulations to compare event likelihood in a world with and without human influence
- Storyline Approach examines the physical processes driving an event and evaluates how anthropogenic forcings modified those processes

### 6.3 Attribution of global warming

Attribution statements of global warming in the three most recent IPCC Assessment reports are:

AR4: “Most of the observed increase in global average temperatures since the mid-20<sup>th</sup> century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations.”

AR5: “It is *extremely likely* that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together. The best estimate of the human- induced contribution to warming is similar to the observed warming over this period.”

AR6: “The *likely* range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019 is 0.8°C to 1.3°C, with a best estimate of 1.07°C. It is *likely* that well-mixed GHGs contributed a warming of 1.0°C to 2.0°C, other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C, natural drivers changed global surface temperature by –0.1°C to +0.1°C, and internal variability changed it by –0.2°C to +0.2°C. It is *very likely* that well-mixed GHGs were the main driver of tropospheric warming since 1979.”

The AR4 and AR5 attribution statements reference the warming to the mid-20<sup>th</sup> century, the period when greenhouse gas emissions began rapidly increasing. The words “most” and “more than half” are deliberately imprecise, potentially ranging from 51 to 99% of the warming – presumably this imprecision is to account for potential structural uncertainties such as natural internal variability. The confidence level increases from *very likely* to *extremely likely* from AR4 to AR5. The structure of the attribution statement in the AR6 is fundamentally different, referencing the warming to the period 1850-1900. The AR6 attribution statement is more precise numerically, but with a lower level of confidence at “likely” – the AR6 attributes essentially all of the warming to increases in greenhouse gases. The most confident statement from the AR6 relates to the tropospheric warming since 1979, using the words “main driver” and “*very likely*.”

There are two areas of substantive criticism of the IPCC assessment of the causes of the recent warming: inadequate assessment of natural climate variability, and inappropriate statistical methods. Both of these issues are relevant not only in context of the main policy-relevant statement of the IPCC concerning attribution of the recent warming, but also because the global warming attribution provides the basis for extreme event attribution

#### 6.3.1 Natural climate variability

The IPCC AR6 states that natural external drivers since 1850-1900 have changed global surface temperature by –0.1°C to +0.1°C, and internal variability has changed it by –0.2°C to +0.2°C – on average, having essentially no net impact on the warming since 1850-1900. This assessment of the contributions of natural variability has been disputed by a number of publications that question the magnitudes of the contributions from solar forcing and internal variability from the large-scale ocean circulations.

If the Equilibrium Climate Sensitivity to CO<sub>2</sub> is low (REF PREVIOUS CHAPTER), then natural climate variability becomes more important in the attribution of the recent warming. Further, if natural variability is higher, then estimates of the Equilibrium Climate Sensitivity from the historical period would be lower (Scafetta, 2023).

Connolly, R.; Soon, W.; Connolly, M.; Baliunas, S.; Berglund, J.; Butler, C.J.; Cionco, R.G.; Elias, A.G.; Fedorov, V.M.; Harde, H.; et al. How Much Has the Sun Influenced Northern Hemisphere Temperature Trends? An Ongoing Debate. *Res. Astron. Astrophys.* 2021, 21, 131.

Soon, W.; Connolly, R.; Connolly, M.; Akasofu, S.-I.; Baliunas, S.; Berglund, J.; Bianchini, A.; Briggs, W.M.; Butler, C.J.; Cionco, R.G.; et al. The Detection and Attribution of Northern Hemisphere Land Surface Warming (1850–2018) in Terms of Human and Natural Factors: Challenges of Inadequate Data. *Climate* 2023, 11, 179. <https://doi.org/10.3390/cli11090179>

Scafetta, N (2023) Empirical assessment of the role of the Sun in climate change using balanced multi-proxy records. *Geoscience Frontiers*,

### *Solar variability*

The IPCC AR5 concluded that the best estimate of radiative forcing due to Total Solar Irradiance (TSI) changes for the period 1750–2011 was  $0.05 \text{ W/m}^2$ . The IPCC AR6 acknowledges a much larger range of estimates of changes in TSI over the last several centuries, stating that the TSI between the Maunder Minimum (1645–1715) and the second half of the twentieth century increased by  $0.7\text{--}2.7 \text{ W/m}^2$ , a range that includes both low and high variability TSI data sets.<sup>41</sup> However, the recommended forcing dataset for the CMIP6 climate model simulations used in the AR6 for attribution studies averages two data sets with low solar variability.<sup>42</sup> (FOOTNOTE REFS FROM CH 8 of book)

While the IPCC AR6 shows a substantially greater solar impact than does the AR5, the overall impact on the climate was assessed to be small compared to anthropogenic forcing of climate change. However, the impact of solar variations on the climate is uncertain and subject to substantial debate CLIMATE DIALOG REF FROM BOOK - something that you would not infer from the IPCC assessment reports.

Exactly how TSI has changed over time has been a challenging problem to resolve. Since 1978, there have been direct measurements of TSI from satellites. However, the data exhibit non-negligible inconsistencies, and interpreting any multi-decadal trends in TSI requires comparisons of observations from overlapping satellites. Substantial uncertainty exists in the TSI composites, particularly owing to a gap in coverage during 1989 to 1992 that prevented direct cross-calibrations between two successive satellites. This rather arcane issue of cross-calibration of two satellite records has profound implications. There are a number of rival composite TSI datasets, disagreeing as to whether TSI increased or decreased during the period 1986–96. Further, the satellite record of TSI is used for calibrating proxy models, whereby past solar variations are inferred from sunspots and cosmogenic isotope measurements.<sup>37</sup>

There is substantial evidence for high solar activity in the second half of the 20<sup>th</sup> century (starting in 1959) and extending into the 1990's, before a decline in the early 21<sup>st</sup> century; this period is often termed the “Modern Maximum.”

Chatzistergos et al. 2023, Solanki et al. 2004, Usoskin et al. 2007

However, some scientists have concluded that it is not possible to be confident of any multi-decadal trend in TSI (Schmutz, 2021).

As a result of this uncertainty, some reconstructions for past values of TSI (since 1750) have low variability, implying a very low impact of solar variations on global mean surface temperature, whereas datasets with high TSI variability can explain more than 70% percent of the temperature

variability since preindustrial times (Soon et al., 2023, Connolly et al, 2021). Hence, the choice of which TSI satellite record used in an analysis can substantially influence how much climate change is attributed to human versus natural forcings.

Chatzistergos, T., et al. (2023). Long-term changes in solar activity and irradiance. *Journal of Atmospheric and Solar-Terrestrial Physics*. [Link](#)

Connolly, R., et al. (2021). How much has the Sun influenced Northern Hemisphere temperature trends? An ongoing debate. *arXiv*. [Link](#)

Connolly et al., “Challenges in the Detection and Attribution of Northern Hemisphere Surface Temperature Trends Since 1850.”

A review article on this topic was recently published in the journal *Research in Astronomy and Astrophysics* (Connolly et al., 2023). The article had 23 co-authors with a range of perspectives, but who were united by their agreement not to take the consensus approach of the IPCC. Rather, the paper emphasized where dissenting scientific opinions exist as well as identifying areas where there is scientific agreement. The authors found that the Sun/climate debate is an issue where the IPCC’s consensus statements were prematurely achieved through the suppression of dissenting scientific opinions.

There is growing evidence that other aspects of solar variability, which are referred to as solar indirect effects, amplify TSI forcing or are independent of TSI forcing. Scafetta et al. (2023) suggests that ~80% of solar influence on climate may stem from non-TSI mechanisms. Candidate processes include: solar ultraviolet changes; energetic particle precipitation; atmospheric-electric-field effect on cloud cover; cloud changes produced by solar-modulated galactic cosmic rays; large relative changes in the magnetic field; and the strength of the solar wind. Solar indirect effects are not included in climate models, although indirect methods of estimating these effects suggest significant influence. However, claims of non-TSI mechanisms influencing climate are uncertain and debated.

□ Scafetta, N., et al. (2023). Empirical assessment of the role of the Sun in climate change using balanced multi-proxy solar records. *Geoscience Frontiers*. [Link](#)

#### *Natural variability of large-scale ocean circulations*

Variations in global mean surface temperature are linked to recurrent large-scale variations in ocean circulation patterns. These circulation patterns include the Atlantic Multidecadal Oscillation (AMO), the Pacific Decadal Oscillation (PDO) and the El Nino-Southern Oscillation (ENSO). These circulation patterns influence ocean heat uptake and heat distribution, and also influence atmospheric circulation patterns and cloud distributions. There is some debate as to whether these variations are strictly internal to the climate system, or whether this variability can have a solar/astronomical origin or can be influenced by large volcanic eruptions.

While climate models simulate the large-scale ocean circulations and internal climate variability, the simulated magnitude in the multi-decadal band is too low in most models relative to observations, and the phasing of the variability in long-term climate simulations is not synced with the actual, observed climate variations. Averaging multiple simulations from climate models effectively averages out the internal variations, leaving only the forced climate variability (e.g., CO<sub>2</sub> forcing). With most of the modern warming beginning in the late 1970’s, the recent 50-year warming is on the same time scale as

the multi-decadal oscillations of the AMO and PDO.

Here are summary statements from the IPCC AR5 and AR6 reports:

"Decadal variability in the Pacific, associated with the PDO or IPO, contributes significantly to regional and global temperature trends, but the relative contributions of internal variability and external forcing are difficult to disentangle in CMIP5 simulations." (AR5 Chapter 10, Section 10.3.1, p. 10- 28)

"Since AR5, there has been increased understanding of the role of internal variability, such as ENSO, PDO, and AMO, in modulating regional climate trends. However, limitations in simulating the exact timing and amplitude of these modes in CMIP6 models contribute to uncertainties in attributing observed changes to anthropogenic forcing (high confidence)." (AR6 Chapter 3, Section 3.7, p. 3-115)

The amplitude of the peak-to-trough impact of the multi-decadal oscillations on global temperatures has been assessed by the IPCC AR6: "The likely range of change due to internal variability is  $-0.2^{\circ}\text{C}$  to  $+0.2^{\circ}\text{C}$ ." This implies a trough-to-peak change of  $0.4^{\circ}\text{C}$ . Over many centuries, any global temperature changes from the troughs and peaks will cancel out, with little to no net impact.

However, with a nominal timescale of 60-80 years for oscillations such as the AMO and PDO, the timing of the peaks and troughs can be confused with the secular trend. This becomes very relevant for attributing the warming for the 50 years since 1975, during which most of the warming has occurred. Even if climate models have the correct amplitude of the multidecadal oscillations, the timing of the peaks and troughs is not adequately simulated, with each model and individual ensemble simulating a different phasing. Once the simulations of the ensemble members and different models are averaged, the natural internal variability contribution is averaged out, effectively cancelling the role of natural internal variability in the attribution process.

The Great Pacific Climate Shift of 1976-1977 was a notable climatic event characterized by an abrupt change in the North Pacific Ocean's atmosphere-ocean system that interacted with global climate patterns. This shift is closely associated with the Pacific Decadal Oscillation (PDO) that oscillates between warm and cool phases over decades. The 1976 shift marked a transition from a predominantly negative (cool) PDO phase (1947–1976) to a positive (warm) phase (1977 through 2000), with significant implications for global and regional climate patterns including the frequencies of El Nino and La Nina events. The Great Pacific Climate Shift coincided with the beginning of a period of accelerated global warming (REF TO A FIG OF GLOBAL TEMP ANOMALIES ELSEWHERE IN DOC) When the Great Pacific Climate Shift is accounted for in climate attribution analyses since 1950, it has been found that 40 percent or more of the warming in the second half of the 20<sup>th</sup> century was caused by natural internal variability (McLean et al, 2009; Tung and Zhou, 2013; Chylek et al., 2016; Scafetta, 2021).

McLean et al. (2009) "Influence of the Southern Oscillation on tropospheric temperature," J. Geophys. Res., 114

Ka-Kit Tung and Jiansong Zhou, "Using Data to Attribute Episodes of Warming and Cooling in Instrumental Records," Proceedings of the National Academy of Sciences 110, no. 6 ( January 23, 2013): 2058–2063, <https://doi.org/10.1073/pnas.1212471110> .



Petr Chylek et al., “The Role of Atlantic Multi-Decadal Oscillation in the Global Mean Temperature Variability,” *Climate Dynamics* 47, no. 9–10 (February 20, 2016): pp. 3271–3279, <https://doi.org/10.1007/s00382-016-3025-7>.

Scafetta, N. Reconstruction of the Interannual to Millennial Scale Patterns of the Global Surface Temperature. *Atmosphere* 2021, 12, 147. <https://doi.org/10.3390/atmos12020147>

### **6.3.2 Statistical methods**

Optimal fingerprinting is a statistical technique that compares observed climate data with climate model simulations to identify patterns (or "fingerprints") associated with human influence. Optimal fingerprinting has been heavily used in the climate literature for establishing attribution; studies applying it have been cited thousands of times, and it has been prominently featured by the IPCC since the Third Assessment Report in 2001.

A series of papers by McKittrick (McKittrick, 2022; McKittrick et al., 2023; McKittrick, 2024) has challenged the statistical methods commonly used in optimal fingerprinting and broader attribution analyses, based on commonly adopted practices in econometrics. These critiques highlight potential biases that could lead to over- or under-estimation of human influence on climate, and problems with the method that reduce confidence in the analysis results.

McKittrick (2022) challenged the methodology introduced by Allen and Tett (1999) for climate change attribution, which is a cornerstone of optimal fingerprinting. McKittrick argues that this methodology violates key conditions of the Gauss-Markov theorem, particularly the requirement that the conditional expectation of errors must be zero. This violation leads to biased and inconsistent estimates of attribution, undermining the reliability of the method.

McKittrick et al. (2023) addresses a paradox in climate attribution studies: standard trend models assume stationary (mean-reverting) error terms, while the climate econometrics literature suggests that if anthropogenic forcing is dominant, temperature trends should exhibit nonstationary (unit root) error terms, which could serve as a "fingerprint" for human influence. McKittrick and co-authors use tools from time series econometrics to resolve this issue, formalizing a hypothesis that temperature series contain both a nonstationary forcing component (due to anthropogenic influences) and a stationary "weather noise" component. This combination can bias unit root tests toward over-rejection, leading to misinterpretations in attribution studies.

McKittrick (2024) addresses the concern that for more than 20 years climate scientists—virtually alone among scientific disciplines—have used Total Least Squares (TLS) to estimate anthropogenic greenhouse gas signal coefficients, despite its tendency to be unreliable unless some strong assumptions hold that in practice are unlikely to be true. Under conditions which easily arise in optimal fingerprinting for climate attribution, TLS yields estimates with large positive biases. Thus, any study that has used TLS for optimal fingerprinting without verifying that it is appropriate in the specific data context has likely overstated the result.

While these analyses do not prove that all of the results from using these methods are wrong, it does show that the basis on which they were believed to be correct is non-existent – hence reducing confidence in the results. McKittrick's work underscores the importance of statistical rigor in attributing climate changes and the need to bridge the gap between econometric and climatological approaches.

## 6.4 Extreme event attribution

The IPCC AR6 provides an ambiguous assessment of the role of global warming in the historical record extreme weather and climate events. Chapter 11 of WG1 states:

"Evidence of observed changes in extremes and their attribution to human influence (including greenhouse gas and aerosol emissions and land-use changes) has strengthened since AR5, in particular for extreme precipitation, droughts, tropical cyclones and compound extremes (including dry/hot events and fire weather). Some recent hot extreme events would have been extremely unlikely to occur without human influence on the climate system."

By contrast, Chapter 12 of WG1 (Table 12.12) paints a different picture – presumably, the expert judgment of different groups of authors for the two chapters came to different conclusions:

- High confidence in an increase in extreme heat events in tropical regions where observations allow trend estimation and in most regions in the mid-latitudes, medium confidence elsewhere
- Medium confidence in a decrease in extreme cold events in Australia, Africa and most of northern South America where observations allow trend estimation
- No evidence of emergence in the historical period of a change in river floods, heavy precipitation, drought, fire weather, severe wind storms, and tropical cyclones

While the overall issue of detecting changes in extreme weather events and their attribution remains ambiguous, most of the activity in this area relates to the attribution of single extreme weather events. The most prominent effort is the World Weather Attribution (WWA) [WEB LINK](#), which is an international research initiative that focuses on extreme event attribution, analyzing how climate change influences the likelihood and intensity of extreme weather events. The approach used by the WWA runs large ensembles of regional climate models to compare the event in today's climate versus a pre-industrial climate without human-caused warming. WWA plays a significant role in linking extreme weather to climate change, using rapid probabilistic attribution to inform public and policy discussions.

However, the WWA's non-peer-reviewed reports, funding ties, and methodological challenges have sparked controversies, with critics questioning the robustness and impartiality of its conclusions. Despite these issues, WWA's work continues to shape climate science and media narratives. Technical criticisms of the approach include: neglect of a formal detection process; an implicit assumption that 100% of the post-industrial warming is caused by CO<sub>2</sub>; and failure to adequately account for natural internal climate variability.

Beyond the issues raised by event attribution approaches, there exist major challenges to the detection step – a step that is commonly skipped, contra to the IPCC's established detection and attribution approach. Extreme events are by definition rare. Many analyses of extreme event types (including the US National Assessment Reports) only evaluate data since 1950 or 1970. However, as emphasized by [Chapter xxx](#), many of the worst extreme weather and climate events in U.S. history occurred in the first half of the 20<sup>th</sup> century and the 19<sup>th</sup> century. And if paleoclimate reconstructions are also considered, it becomes very difficult for an event to pass the detection thresholds of exceeding what is expected from natural variability, particularly if a reasonably sized geographic region is considered.

In spite of these concerns, the U.S. is presently considering something like the WWA, which is being investigated by a NASEM Panel on Attribution of Extreme Weather and Climate Events and their impacts.

<https://www.nationalacademies.org/our-work/attribution-of-extreme-weather-and-climate-events-and-their-impacts>

Extreme weather events can be extreme in terms of the magnitude of individual events, the frequency of events crossing some threshold, or clustering of extreme events. It needs to be acknowledged that extreme events are by definition rare, and short historical records (even century long records) are insufficient for formulating meaningful statistics about return times and event likelihood.

Case studies from two recent high impact extreme events in the U.S. are provided to illustrate the challenges and ambiguities in attributing the frequency and intensity of extreme weather events to human-caused warming.

#### *6.4.1 Case study – 2021 Western North America heat wave*

The 2021 Western North America heat wave was an extreme heat wave that affected much of Western North America in late June 2021. In particular, surface temperature records were set in Portland, OR (115 °F; previous record 107°F) and Seattle, WA (108 °F; previous record 103°F).

The WWA provided the following attribution statements:

<https://www.worldweatherattribution.org/western-north-american-extreme-heat-virtually-impossible-without-human-caused-climate-change/>

<https://www.worldweatherattribution.org/wp-content/uploads/NW-US-extreme-heat-2021-scientific-report-WWA.pdf>

- Based on observations and modeling, the occurrence of this heatwave was virtually impossible without human-caused climate change.
- The event is estimated to be about a 1 in 1000-year event in today's climate.
- The event would have been at least 150 times rarer without human-induced climate change.
- This heatwave was about 2°C hotter than it would have been if it had occurred at the beginning of the industrial revolution (when global mean temperatures were 1.2°C cooler than today).

Mass et al. (2024) summarizes the proximate sequence of compound events leading to the heat wave. There was a record-breaking midtropospheric ridge over the Pacific Northwest, forced by a tropical disturbance in the western Pacific. This produced record-breaking midtropospheric temperatures, strong subsidence in the lower atmosphere, low-level easterly flow that produced downslope warming on regional terrain and the removal of cooler marine air, and an approaching low-level trough that enhanced downslope flow. The event occurred at a time of maximum solar insolation, and drier-than-normal soil moisture. Using a storyline approach, Mass et al. assessed that there is no trend in drought and dry soils in the Pacific Northwest; there is no evidence of global warming producing stronger ridges of high pressure, and no observed trend in heat waves or record temperatures in the region. They concluded that although anthropogenic warming may have contributed as much as 2°F to the magnitude of the event, there is little evidence of further amplification of the event from increasing greenhouse gases.

<https://journals.ametsoc.org/view/journals/wefo/39/2/WAF-D-23-0154.1.xml>

A more sophisticated statistical analysis of a model-based attribution study of this heat wave was conducted by Bercos-Hickey et al. (2022)

<https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2022GL099396> Because this event is a far outlier and far above the bounds of Generalized Extreme Value distributions fitted from historical data, they concluded that estimates of return times, quantitative changes in event magnitude and frequency, and probability of the extreme temperatures such as provided by the WWA are not accurate and are made with low confidence. They found that hindcast attribution methods using an ensemble of regional climate models, combined with Pearl (2009) causal inferences, can provide limited and conditional information about the magnitude of the human influence on this heatwave – they provided a more highly constrained estimate that human activities caused a ~1.4°C–1.8°F increase in the daily maximum temperatures.

The 2021 Western North America heatwave was a rare and unprecedented compound weather event, that broke century-old temperature records by as much as 9°F. While there is little doubt that anthropogenic global warming contributed to the probability and magnitude of the extreme temperatures, the uniqueness of the event challenges quantifying this influence by traditional event attribution methods.

Van Oldenborgh et al. (2022) summarize the challenges of attributing heat waves.

<https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021EF002271>

A warming climate means that a fixed temperature threshold is passed more often, and hence the probability of extreme heat increases. However, land use changes, vegetation change, irrigation, air pollution, and other changes also drive local and regional trends in heatwaves. Sometimes these factors enhance heatwave intensity, but they can also counteract the effects of climate change. Temperature variability is unrealistic in many climate models, and can fail standard quality checks. Therefore, reliable attribution of heatwaves remains a major scientific challenge in many regions, particularly where the moisture budget is not well simulated, and where land surface changes, changes in short-lived forcings, and soil moisture interactions are important.

#### 6.4.2 Case study – Hurricane Harvey rainfall ~~IDONT LOVE THIS EXAMPLE. DELETE? MAYBE SOMETHING ELSE?~~

Hurricane Harvey made landfall in southern Texas on August 24, 2017 as a Category 4 hurricane. The primary damage from Harvey occurred after the storm had been downgraded to a tropical storm and stalled near the coastline with a stationary front along the TX/LA border, dropping torrential and unprecedented amounts of rainfall over Texas. Hurricane Harvey provides an informative example of the challenges of detection for a rare event, and also the complexity of extraneous factors that can influence such an event.

The first issue to consider is detection. Harvey set the record for most amount of rainfall from a continental U.S. landfalling hurricane (60 inches), going back at least to the 1880's when comprehensive records begin (Landsea, 2017). The previous top four rainfall producers for U.S. landfalling hurricanes were: Tropical Storm Amelia (1978) with 48 inches in Texas, Hurricane Easy (1950) with 45 inches in Florida, Tropical Storm Claudette (1979) with 45 inches in Florida, and Tropical Storm Allison (2001) with 40 inches in Texas. Looking more broadly at North American hurricanes that made landfall in Central American and the Caribbean, Roth (2017) identifies the following landfalling hurricanes that produced more rainfall than Harvey: 100 inches in Cuba from Hurricane Flora (1963), 96 inches in Jamaica from the November 1909 Hurricane, 63 inches in Nicaragua from Hurricane Mitch (1998), and 62 inches in Mexico from Hurricane Wilma (2005). Hurricane Harvey's rainfall arguably meets the detection criteria, whereby an attribution analysis is justified, although Harvey's rainfall was far from unprecedented from historic Atlantic hurricane landfalls.

In addressing the attribution of extreme rainfall from a landfalling hurricanes, there are several factors leading to excessive rainfall that aren't associated with temperature. Slow motion of the hurricane near landfall can lead to high amounts of local rainfall (e.g. Wilma – 2005; Harvey – 2017;). Mountains/hills near the coast magnify rainfall potential due to forced upslope flow (e.g. Mitch – 1998). Upper-level troughs and cold fronts can lead to excessive rainfall (e.g. Floyd – 1999). Horizontally large tropical cyclones have larger rain footprints, which can lead to excessive rainfall owing to the longer time frame over which rainfall falls at any one location.

The WWA attribution analysis of Hurricane Harvey's rainfall (Oldenburgh et al., 2017) found that human-caused climate change made the heavy rainfall associated with Hurricane Harvey roughly three times more likely and 15% more intense.

<https://iopscience.iop.org/article/10.1088/1748-9326/aa9ef2#:~:text=This%20would%20indicate%20that%20the,to%20Houston's%20flood%20protectio n%20system.&text=Author%20to%20whom%20any%20correspondence%20should%20be%20addressed>

Several publications based on model simulations have concluded that as much as 40% of the rainfall from Hurricane Harvey was caused by human-caused global warming (Emanuel 2017; Risser and Wehner 2017). The rationale for these assessments was that prior to the beginning of summer of 2017, sea surface temperatures in the western Gulf of Mexico exceeded 86 °F and ocean heat content was the highest on record in the Gulf of Mexico (Trenberth et al. 2017). However, El Niño–Southern Oscillation (ENSO) and Atlantic circulation patterns contributed to this elevated heat content.

Landsea (2017) summarizes the arguments for more rainfall from tropical cyclones traveling over a warmer ocean. Simple thermodynamic calculations suggest that the amount of rainfall in the tropical latitudes would increase by about 4% per °F of sea surface temperature increase. Examining a 300 mile radius circle for nearly all of the rain implies that about 10% more total hurricane rainfall for a warming of 2-2.5 °F. The Gulf of Mexico has warmed about 0.7 °F since 1960. Even if it is assumed that all of this warming is due to manmade global warming suggests that roughly 3% of hurricane rainfall today can be reasonably attributed to manmade global warming. Hence, only about 2 inches of Hurricane Harvey's peak amount of 60 inches can be linked to manmade global warming.

Aryal et al. (2018) examined the contribution of North Atlantic hurricanes to flooding and heavy rainfall across the continental U.S. Their analysis does not point to any significant changes in the magnitude or frequency of floods. They found that the North Atlantic Oscillation (NAO) plays a significant role in hurricane-related extreme rainfall along the U.S. East Coast, while ENSO is most strongly linked to the hurricane-related precipitation in Texas.

With regards to the rainfall associated with landfalling hurricanes, there is no clear signal of increasing rainfall owing to the complexity of the factors contributing to hurricane-induced rainfall.

## **6.5 Summary**

There is an ongoing scientific debate around attribution methods, particularly in attributing extreme weather events to climate change. The IPCC has long cautioned that methods to establish causality in climate science are inherently uncertain and ultimately depend on expert judgement.

There are two areas of substantive criticism of the IPCC assessment of the causes of the recent warming: inadequate assessment of natural climate variability, and inappropriate statistical methods.

Detection of extreme weather events is challenged by their rarity, requiring a long data set and a choice of region and spatial scale to evaluate their occurrence against the background of natural weather and climate variability.

The most robust attribution statements for an extreme event relate to an incremental change (e.g. a temperature change or percent change in rainfall). Statements related to return times, quantitative changes in event magnitude and frequency, and probability of the extremes are not accurate and are made with low confidence. There is no evidence in a change of weather or climate regime patterns from increasing greenhouse gases that would amplify or dampen extreme weather events.

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**From:** Steven Koonin [steven.koonin@gmail.com]  
**Sent:** 5/2/2025 7:16:24 PM  
**To:** 'Roy Spencer' [roywspencer@hotmail.com]; 'Judith Curry' [curry.judith@gmail.com]  
**CC:** 'Ross McKittrick' [ross.mckittrick@gmail.com]; 'Travis Fisher' [travis.scott.fisher@gmail.com]; 'John Christy' [climatemanager60@gmail.com]  
**Subject:** RE: my suggested edits of 4

Don't see that Part II discusses "attribution" - it's about external influences on the climate (through forcing), both natural and anthropogenic. "Attribution" would be to identify observed changes as being causally linked to those influences.

But I agree the text IS deficient on the intrinsic variability of the energy balance.

SEK

---

**From:** Roy Spencer <roywspencer@hotmail.com>  
**Sent:** Friday, May 2, 2025 2:53 PM  
**To:** Steven Koonin <steven.koonin@gmail.com>; 'Judith Curry' <curry.judith@gmail.com>  
**Cc:** 'Ross McKittrick' <ross.mckittrick@gmail.com>; 'Travis Fisher' <travis.scott.fisher@gmail.com>; 'John Christy' <climatemanager60@gmail.com>  
**Subject:** Re: my suggested edits of 4

I feel like there is a disconnect that results from the first 2 Parts, and I am willing to be overruled by the majority on this:

Part I: Direct human influence on ecosystems and the climate

Part II: Climate response to greenhouse gas emissions

Part II addresses "attribution", but the reader might well ask, if there are only **human** influences on climate worthy of description in Part I, then why discuss uncertainties over attribution, if you've only told me about humans influencing the climate?

This is why I previously pointed out that radiative forcing of the climate system can be NATURAL as well as anthropogenic. We have papers published, as does Dick Lindzen, and maybe Judith Curry as well, discussing this.

All you have to do is look at the large variability in TOA radiative flux anomalies vs. surface temperature anomalies, and you can see that most of those flux variations are NOT feedback-related (linearly related to temperature), they instead PRECEDE temperature changes and so are the CAUSE of temperature changes (natural radiative forcing). This is natural radiative forcing (because in the forcing-feedback paradigm of climate change, if it's not feedback, it's forcing).

Unless we are willing to challenge the premise that external (TOA) radiative forcing is ONLY due to humans and volcanoes, we lose the chance to point out, up front, that the climate system can cause its own radiative forcing, and thus climate change.

Do we KNOW this has happened on climate time scales? No. But there is an awful lot of evidence of the RWP, MWP, and LIA. What caused them? We really don't know.

But simply assuming (for example) that the average albedo of Earth has been divinely inspired to be a constant 0.300 for ever and ever amen seems rather presumptuous.

Just my 2 cents.

-Roy

---

**From:** Steven Koonin  
**Sent:** Friday, May 2, 2025 12:53 PM  
**To:** 'Judith Curry'; 'Roy Spencer'  
**Cc:** 'Ross McKittrick'; 'Travis Fisher'; 'John Christy'  
**Subject:** my suggested edits of 4

See attached. Now on to 5!

SEK

---

**From:** Ross McKittrick <ross.mckittrick@gmail.com>  
**Sent:** Friday, May 2, 2025 3:13 PM  
**To:** Roy Spencer  
**Cc:** Steven Koonin; Judith Curry; Travis Fisher; John Christy  
**Subject:** Re: my suggested edits of 4

There are going to be a few places where topics arguably belong in two or more places, and we may find it hard to settle that until we have something like a complete draft to read through at one sitting. I like having the solar and aerosol discussion here as part of the topic of influences (including natural ones) on the climate. I think the important thing about the attribution chapter is explaining that scientists use statistical methods to infer causation in the absence of experimental evidence and there are problems/limitations with any such methods.

I have no trouble reducing the use of quotes. I tend to over-include them because I think people need to see that the cited sources actually said what is attributed, but lengthy inset quotes slow down the flow. And I'm fine switching the Zacharias quote out (there are even shabbier ones from Lean) and replacing it with the Connolly summary.

To Roy's point: I think we make a start at articulating the importance of natural influences in Part I, but if more needs to be said Roy maybe you could try drafting some text.  
Ross

On Fri, May 2, 2025 at 2:53 PM Roy Spencer <roywspencer@hotmail.com> wrote:

I feel like there is a disconnect that results from the first 2 Parts, and I am willing to be overruled by the majority on this:

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Part II: Climate response to greenhouse gas emissions

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But simply assuming (for example) that the average albedo of Earth has been divinely inspired to be a constant 0.300 for ever and ever amen seems rather presumptuous.

Just my 2 cents.

-Roy

---

**From:** Steven Koonin

**Sent:** Friday, May 2, 2025 12:53 PM

**To:** 'Judith Curry'; 'Roy Spencer'

**Cc:** 'Ross McKittrick'; 'Travis Fisher'; 'John Christy'

**Subject:** my suggested edits of 4

See attached. Now on to 5!

SEK

---

**From:** Judith Curry [curry.judith@gmail.com]  
**Sent:** 5/2/2025 7:10:09 PM  
**To:** Roy Spencer [roywspencer@hotmail.com]  
**CC:** Steven Koonin [steven.koonin@gmail.com]; Ross McKittrick [ross.mckittrick@gmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]; John Christy [climatemanager60@gmail.com]  
**Subject:** Re: my suggested edits of 4  
**Attachments:** 6 climate sensitivity JCurry (1).docx

I get what Roy is saying. In my chapter 6 on attribution (attached is a messy version, but you can see where i am going with it; cleaned up version hopefully ready this weekend), key points are about natural variability

On Fri, May 2, 2025 at 11:53 AM Roy Spencer <roywspencer@hotmail.com> wrote:

I feel like there is a disconnect that results from the first 2 Parts, and I am willing to be overruled by the majority on this:

Part I: Direct human influence on ecosystems and the climate

Part II: Climate response to greenhouse gas emissions

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But simply assuming (for example) that the average albedo of Earth has been divinely inspired to be a constant 0.300 for ever and ever amen seems rather presumptuous.

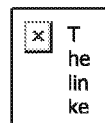
Just my 2 cents.

-Roy

**From:** Steven Koonin  
**Sent:** Friday, May 2, 2025 12:53 PM  
**To:** 'Judith Curry'; 'Roy Spencer'  
**Cc:** 'Ross McKittrick'; 'Travis Fisher'; 'John Christy'  
**Subject:** my suggested edits of 4

See attached. Now on to 5!

SEK



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## 4 Climate Sensitivity to CO<sub>2</sub> Emissions

Atmospheric CO<sub>2</sub> concentration has increased from its pre-industrial level of 280 parts per million (ppm) to around 425 ppm in 2024. Human-caused warming depends not only on the amount of increasing greenhouse gases, but also on how sensitive the climate is to this increase.

Equilibrium Climate Sensitivity (ECS) is defined as the global surface warming that occurs when the concentration of CO<sub>2</sub> in the atmosphere is doubled, relative to pre-industrial levels. The magnitude of the sensitivity of Earth's climate to increasing concentrations of CO<sub>2</sub> is at the heart of the scientific debate on anthropogenic climate change, and also the public debate on the appropriate policy response to increasing CO<sub>2</sub> in the atmosphere.

The magnitude of the Equilibrium Climate Sensitivity is associated with substantial uncertainties, which are highly consequential for policy making. If climate sensitivity to CO<sub>2</sub> concentration is low, then the impacts of increased emissions are expected to be relatively benign, and the benefits of emissions reductions much reduced. If the sensitivity is high, then even moderate increases of CO<sub>2</sub> could produce significant impacts. Climate sensitivity and estimates of its uncertainty are key inputs into the economic models that drive cost-benefit analyses and estimates of the social cost of carbon.

Since the 1979 Charney Report, estimates in international assessment reports have put ECS between 1.5 and 4.5°C of warming for a doubling of CO<sub>2</sub> relative to pre-industrial levels. The ECS range between 1.5 and 4.5°C is characterized by the IPCC AR5 as the *likely* range (66 percent probability); the AR5 stated that ECS is *extremely unlikely* (95 percent probability) to be below 1.0°C and *very unlikely* (90 percent probability) to exceed 6.5°C.

This range of ECS values has remained stubbornly wide, despite many individual studies claiming to narrow it. Most recently, the IPCC AR6 narrowed the *likely* range of ECS to 2.5–4.0°C and the *very likely* range to be between 2.0 and 5.0°C. This narrowing of the range on the low end is disputed.

Understanding of the uncertainties is illuminated by examining the different methods of estimating climate sensitivity and the confounding effects of feedback processes.

### 4.1 Different Ways of Estimating Equilibrium Climate Sensitivity

Climate scientists use multiple lines of evidence to determine the Equilibrium Climate Sensitivity:

- Climate model simulations
- Historical observations
- Paleoclimatic observations
- Process understanding of feedbacks

By itself, the equilibrium warming effect of a doubling of atmospheric CO<sub>2</sub> is slightly more than 1°C (Soden and Held, 2006). The large values of ECS arise from positive feedbacks that amplify the warming effect of CO<sub>2</sub>. Water vapor feedback is positive: a warmer atmosphere may have more water vapor, which itself is a powerful greenhouse gas. Water vapor feedback is partially

canceled by the fact that atmospheric temperature decreases more slowly with height above the Earth's surface when atmospheric water vapor increases. Warmer temperatures also result in less snow and sea ice cover, allowing the Earth to absorb more of the sun's radiation. Some simple estimates of these three feedbacks increase the ECS to around 2°C (Sherwood et al., 2020).

Higher values of ECS arise primarily from positive cloud feedbacks. The magnitude, and even the sign, of cloud feedbacks is the greatest source of uncertainty. Elements of cloud feedback include changes in the latitudinal distribution of clouds, changes in the distribution of cloud height (changes in low versus high clouds), changes to the phase of clouds (ice versus liquid), changes in cloud particle size (associated with changes in concentration and/or composition of aerosol particles), changes in the precipitation efficiency of clouds, and even changes in how clouds are distributed over the daily solar cycle (Curry and Webster, 1999). It is difficult for climate models to simulate any of these cloud processes correctly owing to their small scale, let alone predict how they will change in the future. Further, cloud processes modulate the magnitudes of the water vapor, lapse rate, and the surface albedo feedbacks.

#### **4.2.1 Climate model estimates of ECS**

ECS can be determined from climate model simulations by doubling the concentration of CO<sub>2</sub>, allowing several centuries for the warming to equilibrate. To avoid the necessity of long simulations, effective climate sensitivity is commonly evaluated from a 150-year simulation in response to a sudden quadrupling of CO<sub>2</sub>. The spread of ECS values from the CMIP5 climate models (used in the AR5) was 2.0–4.7°C; the spread has increased for the CMIP6 models (used in the AR6) to between 1.8 and 5.7°C (Chen et al., 2021). Far from the science being settled in relation to the response of the climate system to increasing greenhouse gas concentrations, insofar as it is represented by climate models, uncertainties appear to be growing. The main cause of the overall upward shift in ECS in CMIP6 relative to CMIP5 is a larger positive cloud feedback, driven by changes to the cloud parameterizations in many CMIP6 models (Zelinka et al., 2020).

Climate sensitivity represents an emergent property of climate models—that is, it is not directly parameterized or tuned. However, collections of parameterizations are often chosen to produce an expected value of climate sensitivity, particularly with regards to sub-grid-scale cloud processes. Otherwise plausible models and parameter selections have been discarded because of perceived conflict with this warming rate, or aversion to a model's climate sensitivity being outside an accepted range. For example, Mauritsen and Roeckner (2020) state the following regarding their Max Planck Institute climate model, “We have documented how we tuned the MPI-ESM1.2 global climate model to match the instrumental record of warming; an endeavor which has clearly been successful. Due to the historical order of events, the choice was to do this practically by *targeting an ECS of about 3 K using cloud feedbacks*, [emphasis added] as opposed to tuning the aerosol forcing.” In other words, the modelers chose an ECS value of 3°C and then tuned the cloud parameterizations to match their intended result.

The IPCC AR4 (2007) relied almost exclusively on climate models in its assessment of ECS. The IPCC AR5 (2013) relied on both climate model determinations and determinations from the historical record, noting substantial disagreements between these two methods. Because of concerns about model tuning and the high sensitivity to cloud parameterizations, the IPCC AR6 (2021) did not rely on climate model simulations in their assessment of climate sensitivity, relying

on the other three methods in its assessment.

#### 4.2.2 Data-driven estimates of ECS

Climate sensitivity is also estimated from instrumental records of surface temperatures and ocean heat content, combined with estimates of how climate forcings (e.g., greenhouse gases, solar, volcanoes, aerosols) have changed in the past (Otto et al., 2013). Using this information, an energy budget method is used to deduce the ECS.

The accuracy of the data-driven methods depends on the quality of the input data. Assumptions are needed about ocean heat storage, and the ocean data is inadequate. The greatest source of uncertainty is the amount and composition of aerosol particles and their interactions with cloud radiative properties (the so-called aerosol indirect effect).

Since 2012 many studies have appeared in the literature tackling these various uncertainties. A recurring theme is that ECS estimates based on historical data turn out to be smaller than ECS estimates inferred from climate models (Sherwood and Forest 2024).

Paleoclimate proxies are used to evaluate the sensitivity of past climates, by comparing paleoclimate changes in the Earth's temperatures to estimates of changes in forcings. The two most informative periods are the last glacial maximum (around 20,000 years ago), which was about 3–7°C colder than today, and a mid-Pliocene period (roughly three million years ago), which was 1–3°C warmer than today. The limits on cooling during the last glacial maximum give the best single evidence that high values of climate sensitivity are unlikely. However, paleoclimate estimates are associated with very large uncertainties in the estimated temperatures and forcings. Further, estimates of climate sensitivity based on past climate states may not be representative of the current state of the climate system.

Based on a review article by Sherwood et al. (2020), the IPCC AR6 determined the range of ECS values by integrating the historical, paleoclimate and feedback approaches using a Bayesian analysis method. The IPCC AR6 narrowed the likely range of ECS to 2.5–4.0°C (Chen et al., 2021). Subsequent to the publication of the AR6, Lewis (2023) published an extensive critique of the methodology used in the Sherwood et al. paper to determine the ECS. Key concerns raised by Lewis include errors, outdated input values, and objective versus subjective Bayesian priors in the analysis. Lewis' analysis found that climate sensitivity is estimated to be much lower and better constrained than in the Sherwood et al. analysis – median 2.16°C (1.75–2.7°C in the 17–83 percent *likely* range), and 1.55–3.2°C in the 5–95 percent *very likely* range. Lewis' analysis implies that climate sensitivity is considerably more likely to be below 2°C than above 2.5°C. The IPCC AR6 estimated only a 5 percent probability that ECS was below 2.3°C, whereas Lewis (2023) estimated it to be over 50 percent. The most recent publications on the debate between Sherwood et al. and Lewis further defend their respective positions (Sherwood and Forest, 2024) and (Lewis, 2025).

A recent argument, one which the IPCC AR6 emphasized, is that data-driven ECS estimates might understate the future warming response to GHGs based on a so-called “pattern effect” (Forster et al., 2021). The tropical Pacific is believed to be highly influential on the overall efficiency with which the Earth's climate radiates heat to space, but heat in some parts is more efficiently removed

than from others. If there is a weakening of the west-to-east temperature gradient in the tropical Pacific, the result would be a concentration of warming in a region where heat is less efficiently removed, raising the ECS of the Earth's climate system. Most climate models simulate that rising GHGs will weaken the east-west temperature gradient, which led the IPCC in the AR6 to conclude that data-driven ECS estimates understated the *future* ECS value.

However, Seager et al. (2019) pointed out that, contrary to models, the east-west temperature gradient has been strengthening rather than weakening over time. They further argued that the mechanism predicting otherwise in climate models was based on a faulty characterization of oceanic dynamics and there is no reason to expect the gradient to weaken. A similar argument was recently made by Lee et al. (2024), who concluded that “the trajectory of the observed trend reflects the response to increasing GHG loading in the atmosphere;” in other words GHG warming should lead to a future strengthening rather than a weakening of the temperature gradient. This implies, if anything, that future ECS in a warming climate will be lower than at present.

### 4.3 Transient Climate Response

The Transient Climate Response (TCR) is of greater utility in providing an observational constraint on climate sensitivity. TCR is the amount of warming that would occur at the time when CO<sub>2</sub> doubles, having increased gradually by 1 percent each year over a period of 70 years. Relative to the ECS, observationally- determined values of TCR avoid the problems of uncertainties in ocean heat uptake and the fuzzy boundary in defining equilibrium arising from a range of timescales for the longer-term feedback processes (e.g., ice sheets). TCR is more generally related to peak warming and better constrained by historical warming, than ECS. The IPCC AR6 judged the *very likely* range of TCR to be 1.2–2.4°C (Chen et al., 2021). In contrast to ECS, the upper bound of the TCR is more tightly constrained. For comparison, the TCR values determined by Lewis (2023) is 1.25 to 2.0°C; showing much better agreement with the AR6 values than was seen in a comparison of the ECS values.

A related but more flexible parameter is the Transient Response to cumulative carbon Emissions, or TCRE, which relates global temperature change to the cumulative emissions. TCRE is based upon a linear relationship between global average temperature and cumulative emissions, which holds for cumulative emissions of up to 2 teratons of carbon. For a given value of TCRE, we can calculate the amount of warming expected over a future period in response to scenarios of cumulative carbon emission. The IPCC AR6 provides a *very likely* range for TCRE of 1.0–2.3°C, with a median value of 1.6°C.

### 4.4. Summary

In the past 5 years, there is a growing realization that climate models are not fit for the purpose of determining the sensitivity of the climate to increasing CO<sub>2</sub> (ECS), owing to the dependence of this sensitivity on poorly resolved processes related to clouds and water vapor.

Data-driven approaches using historical data and paleoclimate reconstructions are generally regarded as more reliable for determining ECS, but their reliability is diminished by data inadequacies.

The IPCC AR6 upper bound for the *likely* range of ECS is 4.0°C, lower than the AR5 value of 4.5°C. This lowering of the upper bound seems well justified by the paleoclimatic estimates of the ECS.

The IPCC AR6 lower bound for the *likely* range of ECS is 2.5°C, substantially higher than the AR5 value of 1.5°C. This raising of the lower bound of the *likely* range of ECS has received a substantial challenge from the analysis of Lewis (2023, 2025) that finds the lower bound of the likely range to be 1.75°C with a median value of 2.16°C.

Estimates of the transient climate response (TCR; TCRE) are more tightly constrained on the upper bound than the ECS.

It is our assessment that a *likely* range for ECS of 1.75 to 4.0°C has the best justification.



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27. Nicholas Lewis, "Objectively Combining Climate Sensitivity Evidence."
28. Rajendra K. Pachauri and Leo Meyer, *Climate Change*.
29. Nicholas Lewis, "Objectively Combining Climate Sensitivity Evidence."
30. Nicholas Lewis, "Comment on 'Can Uncertainty in Climate Sensitivity Be Narrowed Further?' by Sherwood and Forest (2024)."

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**From:** Roy Spencer <roywspencer@hotmail.com>  
**Sent:** Friday, May 2, 2025 2:53 PM  
**To:** Steven Koonin; 'Judith Curry'  
**Cc:** 'Ross McKittrick'; 'Travis Fisher'; 'John Christy'  
**Subject:** Re: my suggested edits of 4

I feel like there is a disconnect that results from the first 2 Parts, and I am willing to be overruled by the majority on this:

Part I: Direct human influence on ecosystems and the climate

Part II: Climate response to greenhouse gas emissions

Part II addresses "attribution", but the reader might well ask, if there are only **human** influences on climate worthy of description in Part I, then why discuss uncertainties over attribution, if you've only told me about humans influencing the climate?

This is why I previously pointed out that radiative forcing of the climate system can be NATURAL as well as anthropogenic. We have papers published, as does Dick Lindzen, and maybe Judith Curry as well, discussing this.

All you have to do is look at the large variability in TOA radiative flux anomalies vs. surface temperature anomalies, and you can see that most of those flux variations are NOT feedback-related (linearly related to temperature), they instead PRECEDE temperature changes and so are the CAUSE of temperature changes (natural radiative forcing). This is natural radiative forcing (because in the forcing-feedback paradigm of climate change, if it's not feedback, it's forcing).

Unless we are willing to challenge the premise that external (TOA) radiative forcing is ONLY due to humans and volcanoes, we lose the chance to point out, up front, that the climate system can cause its own radiative forcing, and thus climate change.

Do we KNOW this has happened on climate time scales? No. But there is an awful lot of evidence of the RWP, MWP, and LIA. What caused them? We really don't know.

But simply assuming (for example) that the average albedo of Earth has been divinely inspired to be a constant 0.300 for ever and ever amen seems rather presumptuous.

Just my 2 cents.

-Roy

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**From:** Steven Koonin  
**Sent:** Friday, May 2, 2025 12:53 PM  
**To:** 'Judith Curry'; 'Roy Spencer'  
**Cc:** 'Ross McKittrick'; 'Travis Fisher'; 'John Christy'  
**Subject:** my suggested edits of 4

See attached. Now on to 5!

SEK

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**From:** Judith Curry [curry.judith@gmail.com]  
**Sent:** 5/2/2025 6:42:20 PM  
**To:** Steven Koonin [steven.koonin@gmail.com]  
**CC:** Roy Spencer [roywspencer@hotmail.com]; Ross McKittrick [ross.mckittrick@gmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]; John Christy [climatemanager60@gmail.com]  
**Subject:** Re: my suggested edits of 4  
**Attachments:** 4.AnthropogenicRF.Apr29 [SEK] JC.docx

My comments on ch 4 are attached, I have some major issues:

Some of what is in this section (esp solar, aerosols) belongs either in climate sensitivity or attribution chapter, not the radiative forcing chapter. (note: my attribution chapter is finished, just sorting out the references). The key aerosol radiative forcing issue (aerosol indirect effect) is not even mentioned.

One possible solution to the aerosol issue is a separate chapter, that includes the impact of recent sulfate rules for ship emissions (there are actually many topics for such a chapter). I could take this on

I object to the Zacharias (2014) and the quote, attributing motives to climate scientists. This would be a very bad look for us

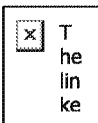
I also think that most of the direct quotes shouldn't be included. These should be reserved for IPCC conclusions or something particularly profound: we don't want to include quotes that come across like "skeptics trying to score cheap points by quoting other skeptics"

On Fri, May 2, 2025 at 10:53 AM Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)> wrote:

See attached. Now on to 5!

SEK

--



Judith Curry, President  
CFAN - Climate Forecast Applications Network  
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<http://www.cfanclimate.net>

## 4 Human influences on the climate

### 4.1 Components of radiative forcing and their history

#### 4.1.1 Historical radiative forcing

A changing climate has been the norm throughout the Earth's 4.6-billion-year history. The Earth's temperature and weather patterns change naturally over timescales ranging from decades to millions of years. Natural variations in the surface climate originate in two ways. Internal climate fluctuations associated with circulations in the atmosphere and ocean produce exchanges of energy, water, and carbon between the atmosphere, oceans, land, and ice. External influences on the climate system include variations in the energy received from the sun and the effects of volcanic eruptions. Human activities influence climate through changing land use and land cover. Humans are also changing the composition of the atmosphere by increasing emissions of CO<sub>2</sub> and other greenhouse gases and by altering the concentrations of aerosol particles in the atmosphere.

The earth is warmed by the sunlight it absorbs and cooled by the radiative heat it emits to outer space. Averaged over Earth, each of these processes involve power flows of about 240 Watts per square meter (W/m<sup>2</sup>). When they are in balance, there are no net external causes of warming or cooling. Human (and some natural) influences on the climate alter this balance and so cause the climate to change.

Influences on the energy balance are quantified by "radiative forcing", the extent to which they disturb the warming/cooling balance; a positive forcing warms while a negative forcing cools. The IPCC's estimated history of major components of radiative forcing since 1750 is shown in the following two figures from the IPCC AR6.

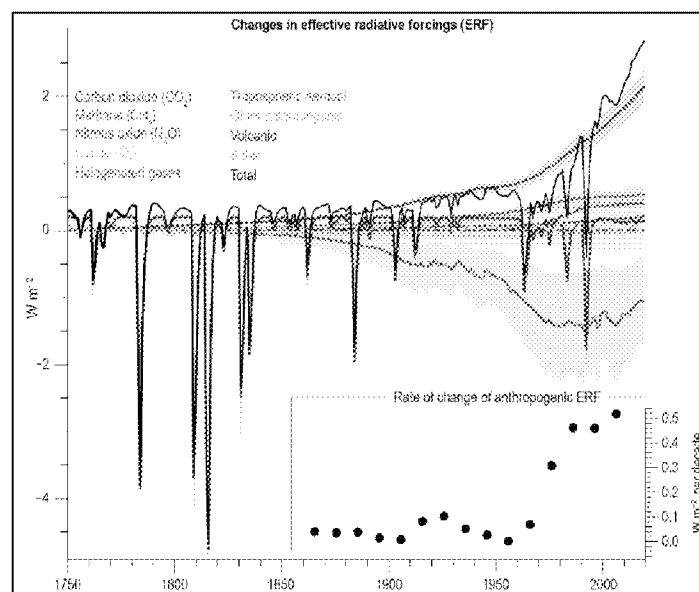


Figure 4.1.1: IPCC estimates of radiative forcing components over time. Source: <https://www.ipcc.ch/report/ar6/wg1/figures/chapter-2/figure-2-10/>

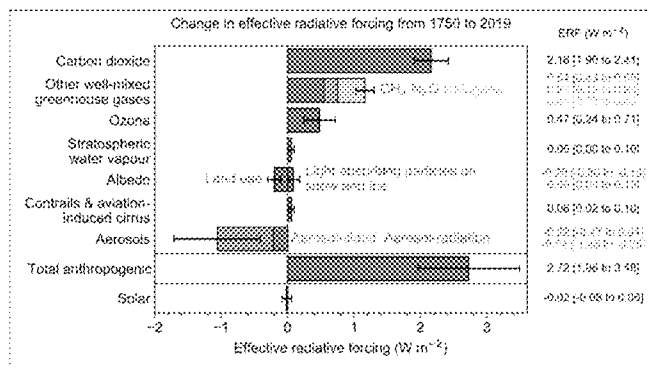


Figure 4.1.2 IPCC estimates of radiative forcing component changes from 1750 to 2019. Source: <https://www.ipcc.ch/report/ar6/wg1/figures/chapter-7/figure-7-6/>

These graphs show that the total radiative forcing is comprised of natural and anthropogenic components. Carbon dioxide is the largest human influence on the climate and the one most relevant to the effects of energy-using systems like motor vehicles. It exerts a warming influence by decreasing the cooling power of the atmosphere. Emissions of CO<sub>2</sub> are accumulating in the atmosphere, as described in the following section, so that the warming influence is increasing. Other greenhouse gases (methane, nitrous oxide, halogens, and ozone), which act similarly, currently add another 75% to CO<sub>2</sub>'s warming. Aerosols exert a cooling effect, although with large uncertainties in the way they catalyze the formation of reflective clouds. As a result, understanding of the causes of recent warming requires not just identifying the warming effects of CO<sub>2</sub>, but also the more uncertain cooling effects of sulfate aerosols.

IS THIS PARA MORE RELEVANT TO RADIATIVE FORCING OR TO ATTRIBUTION CHAPTER The IPCC views the role of the sun as negligible, based on their preference for reconstructions that imply minimal solar change since preindustrial times. Connolly *et al.* (2021) reviewed sixteen different Total Solar Irradiance (TSI) reconstructions in the literature covering the 1600-2000 interval; they vary from almost no change in TSI to a relatively large upward trend. Connolly *et al.* point out that the variation in TSI reconstructions combined with variations in surface temperature reconstructions implies pairings can be found that are consistent with either no or most 20<sup>th</sup> century warming being attributable to the sun. A particularly thorny issue is the gap in the TSI data between 1989 and 1991 due to a delay in the launch of a monitor after the Space Shuttle Challenger disaster on January 28 1986, which prevented a replacement satellite from being launched in time to overlap with, and its readings to be intercalibrated with, the prior system

(Zacharias 2014, Scafetta et al. 2019). The question of whether there is an upward trend in TSI over 1978 to 2018 comes down to how the missing data in that gap are filled. ~~That being the case it is noteworthy that Zacharias (2014) observes the solar research community has been motivated by a desire to downplay any potential role of the sun in climate change so as not to detract from arguments for greenhouse gas abatement:~~ THIS IS DUPLICATIVE OF SOME OF THE MATERIAL I HAVE IN THE ATTRIBUTION CHAPTER.

~~A conclusive TSI time series is not only desirable from the perspective of the scientific community, but also when considering the rising interest of the public in questions related to climate change issues, thus preventing climate skeptics from taking advantage of these discrepancies within the TSI community by, e.g., putting forth a presumed solar effect as an excuse for inaction on anthropogenic warming.~~

~~(Zacharias 2014)~~

I'M NOT THRILLED WITH THE ZACHARIAS REF THIS SEEMS LIKE CHEAP POINTS SCORING, AND ATTRIBUTING MOTIVES TO OTHER PEOPLE IS A BAD MOVE. I THINK THE STATEMENT FROM CONNOLLY IS BETTER:

Connolly et al. (2023) found that the Sun/climate debate is an issue where the IPCC's consensus statements were prematurely achieved through the suppression of dissenting scientific opinions.

The other natural forcing component is largely volcanic aerosols, which exert an episodic cooling influence.

The anthropogenic forcing component was negligible before about 1900 and has increased steadily since, rising to almost 3 W/m<sup>2</sup> today. However, this is still only about 1 percent of the unperturbed radiation flows, making it a challenge to isolate the effects of anthropogenic forcing since state-of-the-art satellite estimates of global radiative energy flows are only accurate to a few W/m<sup>2</sup>. Natural sources of global energy imbalance other than volcanoes are not included in these graphs because they remain largely unknown.

#### 4.1.2 Future radiative forcing

Carbon dioxide's warming influence depends upon how much "extra" CO<sub>2</sub> accumulates in the atmosphere- i.e., its concentration. The CO<sub>2</sub> level as recorded at the Mauna Loa observatory in Hawaii is generally used as the representative global average concentration. The data are



available online at <https://gml.noaa.gov/ccgg/trends/index.html>. The concentration was about 316 ppm at the start of the record in 1959 and is now about 425 ppm, a 34 percent increase.

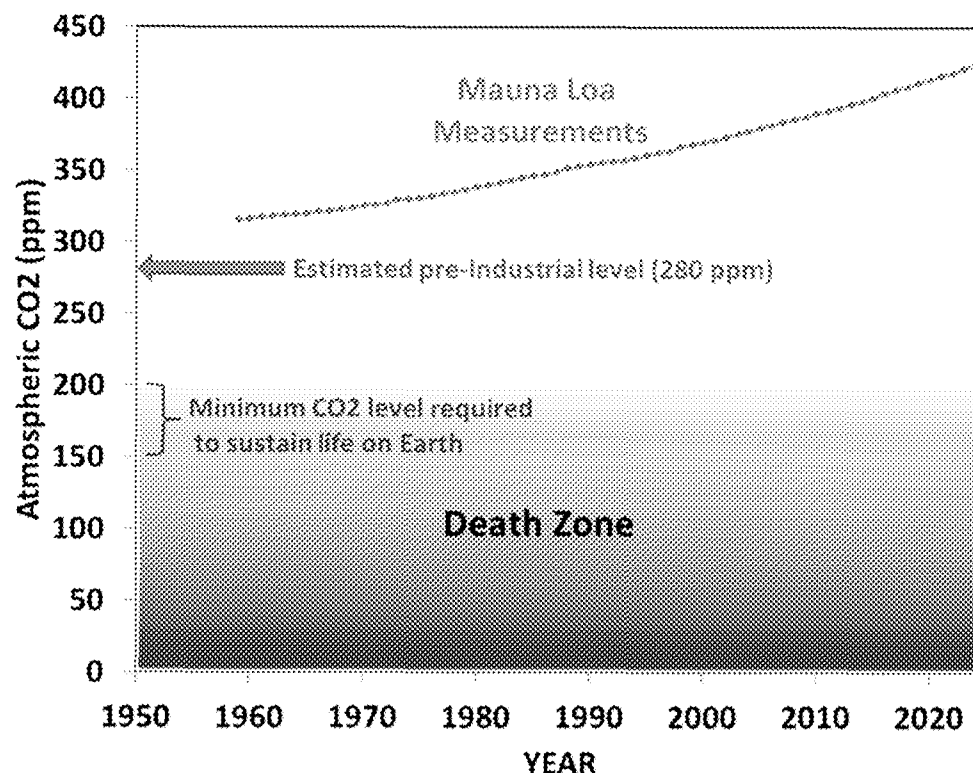


Fig. 4.1.3 Yearly average atmospheric CO<sub>2</sub> concentrations (1959-2024) measured at Mauna Loa, HI (green) compared to the estimated pre-Industrial CO<sub>2</sub> concentration of 280 ppm, and the estimated minimum levels required to sustain life on Earth (150 to 200 ppm). Need source

The annual increase in concentration is only about half of the CO<sub>2</sub> emitted because land and ocean processes absorb “excess” CO<sub>2</sub> at a rate approximately 50% of human emissions. Thus, future concentrations, and hence future human influences on the climate, depend upon two components: (1) future rates of global human CO<sub>2</sub> emissions, and (2) how fast the land and ocean remove extra CO<sub>2</sub> from the atmosphere. We discuss each of these in turn.

## 4.2 Future emission scenarios and the carbon cycle

### 4.2.1 Emission scenarios

Assessing the future dangers of GHG emissions requires assumptions about what those emissions will be. Future emissions, and hence human influences on the climate, will depend upon future demographics, economic progress, regulation, and the energy and agricultural technologies in use. Various assumptions about each of those lead to projections of greenhouse gas emissions and concentrations, aerosol concentrations, and changes in land use, which ultimately can be combined into assumptions about anthropogenic radiative forcing.

Because of the great uncertainties about these many factors in the the decades to come, instead of making precise predictions of future concentrations, the IPCC has created various sets of scenarios meant to span a plausible range of possibilities for population, economy, technology, and so on. Recent versions of the scenarios are labeled by a number indicating the anthropogenic radiative forcing expected in 2100 under that scenario. Thus, a scenario labeled with a “6” corresponds to 6 W/m<sup>2</sup> of human-induced radiative forcing (warming) at the end of the century. (Recall current anthropogenic radiative forcing is about 2.7 W/m<sup>2</sup>.)

Although the IPCC does not put its emission scenarios forward as forecasts they are often treated as such. Comparisons of past scenario groups against observations shows a tendency for IPCC emission projections to overstate actual subsequent emissions. For the IPCC Third and Fourth Assessment Reports a set of emission projections from the *Special Report on Emission Scenarios* were used and hence were referred to as the SREP scenarios. McKittrick *et al.* (2012) showed that, when converted to per capita terms, the SREP scenario distribution was skewed upwards and incompatible with observed trends. McKittrick and Wood (2013) further showed that global energy market dynamics constrained global per capita CO<sub>2</sub> emissions to an extent not reflected in IPCC scenarios. The bias of the SRES scenarios was confirmed by the later analysis in Hausfather *et al.* (2019) who showed that observed atmospheric CO<sub>2</sub> concentrations tracked the low end of the SRES range.

For the Fifth Assessment Report the IPCC developed a new set of scenarios called the Representative Concentration Pathways (RCP). These were identified by a number representing the increase in forcing and were thus called RCP2.6, RCP4.5, RCP6.0 and RCP8.5. RCP2.6 (implying a radiative forcing in 2100 of 2.6 W/m<sup>2</sup>) projects a GHG concentration pathway leading to warming well below 2 C. At the other end of the scale RCP8.5 is an extreme outcome implying nearly 5 C warming just in this century.

RCP8.5 came to be referred to as the no-policy baseline, or “business-as-usual” scenario in both the academic literature and popular media. It was therefore used to generate the reference outcome supposedly representing the 21<sup>st</sup> century world in the absence of emission reduction policies. But RCP8.5 was intended as a low-probability high emissions scenario and its usage as a

business-as-usual baseline has been criticized as grossly misleading.<sup>1</sup> Hausfather and Peters (2020) writing in a commentary in *Nature* magazine, pointed out that RCP8.5 was developed as an extreme worst-case, and its misuse as a “business as usual” baseline has resulted in a large number of misleading studies and media reporting:

RCP8.5 was intended to explore an unlikely high-risk future. But it has been widely used by some experts, policymakers and the media as something else entirely: as a likely ‘business as usual’ outcome. A sizeable portion of the literature on climate impacts refers to RCP8.5 as business as usual, implying that it is probable in the absence of stringent climate mitigation. The media then often amplifies this message, sometimes without communicating the nuances. This results in further confusion regarding probable emissions outcomes, because many climate researchers are not familiar with the details of these scenarios in the energy-modelling literature.

(Hausfather and Peters 2020)

The implausibility of the RCP8.5 scenario was examined by Burgess *et al.* (2021). They noted that RCP8.5 has already diverged from observed energy use trends, and the near future trends diverge sharply from those of the International Energy Agency (IEA) which provides market-based projections of energy use for coming decades. IEA trends are based on plausible extrapolations of current economic and demographic trends, and the results run below the entire envelope of RCP projections, implying not only that RCP8.5 is dubious, but even lower emission scenarios are looking unlikely. Burgess *et al.* comment (p. 8):

Beyond 2040, if the trends anticipated by energy agency forecasts continue, carbon intensity will continue diverging from AR5 and SSP baselines—especially from higher-emission scenarios such as RCP8.5, due to the assumptions about fossil-fuel expansion in these scenarios that are increasingly implausible.

Widespread use of RCP8.5 has created an alarmist bias in the climate impacts literature. The extent of this problem was confirmed in a literature analysis by Pielke Jr. and Ritchie (2020). They found (p. 32) that some 16,800 scientific papers published between 2010 and 2020 used the RCP8.5 scenario, with about 4,500 of the articles (p. 16) linking RCP8.5 with the concept of “business-as-usual”. Their analysis showed how RCP8.5 was misused not only by individual researchers, but also by influential science agencies like the IPCC and the US National Climate Assessment (USNCA), which has directly led to misleading coverage in prominent media outlets. They offer the following example (p. 30):

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<sup>1</sup> This extreme scenario is useful for modelers, since a large forcing generates a large response (warming) making it easier to assess a model’s sensitivity. But that’s very different than claiming it is a plausible future.

The USNCA employed RCP8.5 as a baseline scenario, despite warning against such use, and compared it to RCP4.5 throughout its report to generate quantitative economic estimates of the benefits of mitigation. In a front-page story, the *New York Times* promoted the report's misuse of RCP8.5 as a baseline scenario:

“A major scientific report issued by 13 federal agencies on Friday presents the starkest warnings to date of the consequences of climate change for the United States, predicting that if significant steps are not taken to rein in global warming, the damage will knock as much as 10 percent off the size of the American economy by century's end.”

Pielke and Ritchie (2020) reported new studies using RCP8.5 were appearing in the literature at a rate of about 20 per day, with about two per day specifically linking RCP8.5 and “business as usual.” They conclude (p. 34) that the climate research community has spent a decade “committing scientific resources to science fiction” (emphasis added):

“Derived estimates from RCP8.5 as “business as usual” such as future climate impacts, the impacts avoided from mitigation and the cost effectiveness and benefits of mitigation have no real-world meaning... **The scientific literature has become imbalanced in an apocalyptic direction.**

(Pielke Jr. and Ritchie p. 34)

The IPCC later converted the RCP scenarios to the “Shared Socioeconomic Pathway” or SSP scenarios, but these have continued the pattern of bias shown with the RCP and SRES scenarios. Figure 3.1.4 was generated using the Resources for the Future Global Energy Outlook tool (RFF 2025). The black line shows total global observed CO<sub>2</sub> emissions compiled by the International Energy Agency (IEA). The solid green line is the emission trajectory developed by BP Energy taking account of current emission control policies and global energy use outlooks. It overlaps a solid black line which represents the emission projection from the IEA also taking account of energy use projections and current policies. The dashed lines show the range of IPCC SSP policies. As of 2023 global CO<sub>2</sub> emissions have been tracking well below the SSP scenarios especially the two highest ones (SSP5-8.5 and SSP3-7.0).

Carbon dioxide emissions (Million metric tons), by Outlooks & Scenarios. Filtered by Region: World; Fuel: All; Outlook: 2023 Shell (Sky 2050).

Source: RFF Global Energy Outlook at [www.rff.org/geo](http://www.rff.org/geo)

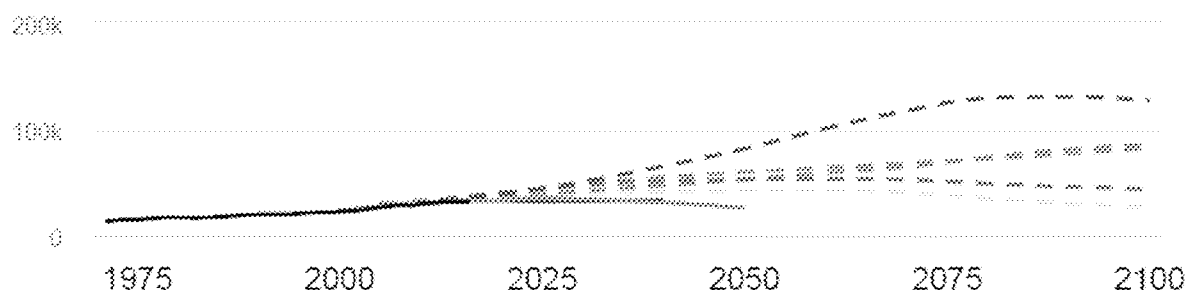


Figure 4.2.1. Observed and projected CO<sub>2</sub> emissions. Source: RFF (2025).

#### 4.2.2 The carbon cycle relating emissions and concentrations

Global carbon cycle models relate concentrations to emissions using estimates of various land and ocean processes that remove CO<sub>2</sub> from, and emit CO<sub>2</sub> into, the atmosphere. Our understanding of these processes was reviewed by Crisp et al. (2021). The natural fluxes of CO<sub>2</sub> in and out of the Earth's surface are very large, many times anthropogenic emissions, but those CO<sub>2</sub> sources and sinks were assumed to be in approximate balance in pre-Industrial times, as evidenced by relatively constant levels of atmospheric CO<sub>2</sub> in centuries past derived from air bubbles in ice cores. This is one of several reasons why increasing atmospheric CO<sub>2</sub> levels are believed to be dominated by anthropogenic sources.

Specifically, fossil fuel burning (and to a lesser extent land use [biomass burning] and cement production) has led to steadily increasing CO<sub>2</sub> levels in the atmosphere, as shown in Fig. 1.2.1. CO<sub>2</sub> emissions from fossil fuel burning is a small fraction of the natural carbon cycle components. About 44,000 Gigatonnes of carbon-equivalent (GtC) are stored in the atmosphere and oceans, mostly in the form of CO<sub>2</sub>. (Ciais et al. 2013). Between 150 and 200 GtC are released naturally each year through oceanic outgassing and land-based processes like plant decay and animal respiration. A variable but roughly equivalent amount is absorbed each year by the land and oceans, with a small net loss from the atmosphere because the formation of deep ocean sediment sequesters some carbon permanently. Global fossil fuel consumption and cement manufacture released about 10.3 GtC in 2023, up from 6.2 GtC in 1990 (Ritchie et al.

2024). Of this, about half is naturally sequestered through plant growth and oceanic uptake while the remainder, about half, adds to the atmospheric stock (Ciais et al. 2013).

As noted, each year natural processes remove a net amount of CO<sub>2</sub> equivalent to about 50% of global emissions. Thus, anthropogenic CO<sub>2</sub> emissions average twice what is required to explain the atmospheric rise in CO<sub>2</sub> concentration. The near-constancy of that 50% fraction (the “airborne fraction”) also means that the more CO<sub>2</sub> humanity produces, the faster Nature removes it from the atmosphere. That 50% fraction changes somewhat from year to year due to natural carbon cycle imbalances from El Nino, La Nina, and varying weather patterns. There was also a substantial additional reduction in atmospheric CO<sub>2</sub> after the 1991 eruption of Mt. Pinatubo, a curious result that has yet to be explained (Angert et al., 2004).

The main processes which remove excess CO<sub>2</sub> from the atmosphere are increased production of land vegetation (especially at high latitudes), some increase in the sequestering of carbon in soils, and uptake of CO<sub>2</sub> by the ocean due to the increasing partial pressure of atmospheric CO<sub>2</sub> over that of CO<sub>2</sub> dissolved in the ocean. All twenty land carbon cycle models tracked by the Global Carbon Project (Friedlingstein et al., 2024) show land processes have been removing excess CO<sub>2</sub> at an increasing rate since 1959. This is consistent with a “global greening” phenomenon observed by satellites since monitoring of global greenness began in the 1982. This greening has been traced to CO<sub>2</sub> fertilization and greater drought tolerance of plants exposed to elevated CO<sub>2</sub> levels. While there had been some uncertainty whether a greening trend continued beyond 2000, the most recent research (Chen et al., 2023) has shown continued greening, with even some slight acceleration since 2000. Global greening is discussed further in Section 3.1.

While land vegetation has been responding positively to more atmospheric CO<sub>2</sub>, uptake of extra CO<sub>2</sub> by ocean biological processes remains too uncertain to be reliably measured. Our current understanding of these and many more carbon cycle processes was reviewed by Crisp et al. (2021).

Public policy can only change the rate of emissions, not the concentration in the atmosphere. For criteria air contaminants the rate and concentration are closely connected because the lifetime is short and the concentration is small. When emissions are reduced the local pollution concentration drops rapidly, usually on a time scale of a few days. Not so with the global average CO<sub>2</sub> concentration since global carbon cycle is vast and slow. A change in local emissions today will only have a very small global effect, and only after a long time lag. After a pulse (release) of CO<sub>2</sub> emissions to the atmosphere only about 40 percent ( $\pm 15\%$ ) of the extra CO<sub>2</sub> will have been sequestered after twenty years. After a thousand years about 75 percent ( $\pm 10\%$ ) will have been sequestered, and the remainder will gradually be removed over the ensuing tens of thousands of years (Ciais et al. 2013, pp. 472-473). Consequently US CO<sub>2</sub> emission reductions will take decades or centuries to lead to a reduction in the global CO<sub>2</sub> concentration.

To reduce the atmospheric stock of CO<sub>2</sub>, assuming the entire increase is anthropogenic, would require emissions to fall below the natural sequestration rate. Since that rate has been averaging about 50% of emissions, a reduction of global emissions by 50% would (at least temporarily) halt the rise in atmospheric CO<sub>2</sub>. The 1997 Kyoto Protocol proposed to cap industrial nations' CO<sub>2</sub> emissions at a modest five percent below 1990 levels by the year 2012. Even though this policy ended up being too costly for most nations to implement, full compliance would not have substantially reduced atmospheric CO<sub>2</sub> levels. It would only have slightly slowed CO<sub>2</sub> growth, reaching the projected 2100 level in 2105 instead (Wigley 1998). Similarly, Lomborg (2016) used the widely-used MAGICC climate model and showed that full compliance with the Paris Accord would not stop warming, it would only prevent about 0.1C warming and delay hitting the baseline year 2100 temperature levels by about a decade.

Thus, in contrast with conventional air pollution control, local actions yield extremely small local effects, and only after a long time lag. The practice of referring to unilateral US reductions as "combatting climate change" or "taking action on climate" reflects a profound misunderstanding of the scale of the issue. The scale problem is compounded by recognizing that US motor vehicles account only for about 4 percent of global CO<sub>2</sub> emissions so even a fifty percent reduction in those emissions would have a vanishingly small effect on the global climate.

#### 4.3 Aerosols and the uncertainties associated with them

The role of this chapter should be to address radiative forcing – not ECS or warming attribution. I think that the material in this section should be moved to ECS or attribution. There is huge uncertainty in the aerosol indirect effect, which relates directly to radiative forcing. I can write up something on this

THIS PARA SHOULD BE DELETED HERE, THIS IS COVERED IN THE ATTRIBUTION CHAPTER The climate's sensitivity to CO<sub>2</sub> (as quantified by ECS, the Equilibrium Climate Sensitivity<sup>2</sup>) is uncertain in part because the anthropogenic radiative forcing is ~~uncertain because the net forcing~~ results from (at least) two counteracting components: warming from GHG's and cooling from aerosols. The observed warming can therefore be made to be consistent with a wide range of pairs of these forces. In the following schematic, the net warming represented by the red

---

<sup>2</sup> ECS is formally defined as the increase in equilibrium global average surface temperature resulting from a doubling of the atmospheric CO<sub>2</sub> concentration above its pre-industrial value of 280 ppm. Estimates of ECS are reviewed in Section XX.

arrow could be due to the High GHG warming/strong aerosol cooling pair, or the Low GHG warming/weak aerosol cooling pair, or something in between.

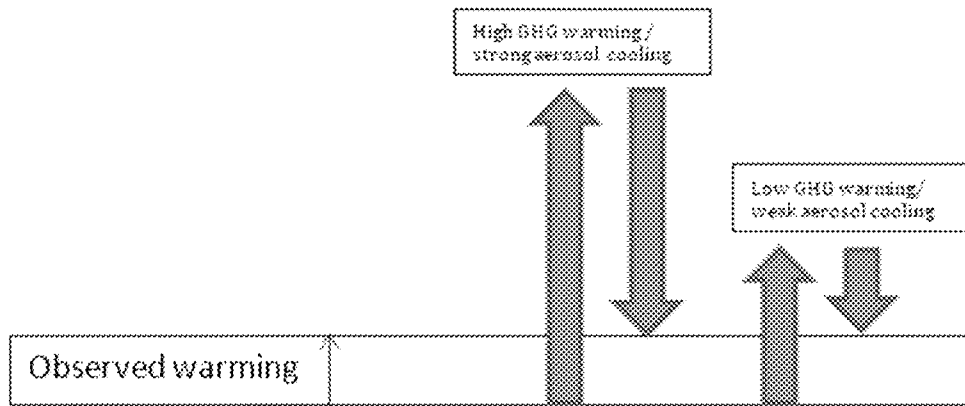


Figure 4.3.1: High and low climate sensitivity to GHGs can be reconciled with the same warming by assuming an offsetting aerosol cooling effect.

THIS CAN GO IN ECS CHAPTER Research on the strength of aerosol cooling is therefore central to more precise ECS estimates. Lewis and Curry (2018) note that after the IPCC AR5 was published in 2013, eleven studies appeared in the scientific literature all finding that aerosol cooling was weaker than had previously been conjectured. Combining the updated aerosol estimates with greenhouse gas, ocean heat uptake and atmospheric warming data from the IPCC and applying standard empirical methods, Lewis and Curry (2018) estimated the best-guess ECS to be 1.66°C with a 95 percent uncertainty range of 1.15 °C – 2.7°C. They concluded that based on the ECS values derived from most IPCC climate models were incompatible with observed data.

There has been further evidence of lower aerosol cooling (implying lower ECS) such as Liu et al. (2021). THIS COULD BE MADE TO BE RELEVANT TO RADIATIVE FORCING CHAPTER These authors tested the hypothesis that aerosols from wildfires has increased since before the 20<sup>th</sup> century which, if true, would mean there had to have been relatively strong CO<sub>2</sub> warming over that period offsetting the aerosol cooling. They examined soot layers in ice cores extracted from Antarctica and South America and determined that wildfire activity prior to the 20<sup>th</sup> century was higher than previously believed. Instead of wildfire activity rising steadily from the 1700s to the present, it was high all the time, thus contradicting the hypothesized aerosol cooling trend in



the Southern Hemisphere during the 20<sup>th</sup> century. They pointed out how this finding relates to the climate sensitivity issue:

Accurate estimates of aerosol radiative forcing are also crucial for better understanding the transient climate response (TCR) and equilibrium climate sensitivity (ECS) to increasing CO<sub>2</sub> and more accurate projection of future climate change. The negative aerosol radiative forcing can, in part, cancel out the positive forcing of increasing greenhouse gases and contribute to the uncertainty of total radiative forcing. An overly large aerosol cooling implies that models might overestimate TCR and ECS to reproduce historical temperature response. A recent study using one of the latest-generation CMIP6 climate models (E3SM) suggested that reducing both the magnitudes of negative aerosol radiative forcing and climate sensitivity yields a better agreement with the observed historical record of the surface temperature.

(Liu et al. 2021)

~~Liu told the UK Daily Mail<sup>3</sup>~~

~~Climate scientists have known that the most recent generation of climate models have been over-estimating surface temperature sensitivity to greenhouse gasses, but we haven't known why or by how much. This research offers a possible explanation.~~

I really think we should limit direct quotes to IPCC or other official docs, or something that is especially profound.

More evidence pointing to weak aerosol cooling was reported by Wang *et al.* (2021). They noted that the strength of aerosol cooling is partly mediated by cloud behavior and differs between the North and South Hemispheres because of the different density of aerosol emissions. This allowed them to construct another test of climate model validity, which came out in favor of low ECS models. In their words:

Since anthropogenic aerosols primarily concentrate in the Northern Hemisphere, strong aerosol-cloud interaction models produce an interhemispheric asymmetric warming. We show that the observed warming asymmetry during the mid to late 20th century is more consistent with low ECS (weak aerosol indirect effect) models. PARAPHRASE, DIRECT QUOTE NOT NEEDED

Wang et al. (2021)

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<sup>3</sup> Available online at <https://www.dailymail.co.uk/sciencetech/article-9629919/Climate-change-warming-effect-greenhouse-gases-overestimated-ice-core-study-suggests.html>

THIS PARA IS AN ATTRIBUTION STATEMENT, NOT A FORCING STATEMENT To summarize, quantifying warming due to CO<sub>2</sub> requires understanding the strength of aerosol cooling. While that latter is uncertain a substantial body of recent evidence points to it being relatively weak, implying that CO<sub>2</sub> warming is likewise weak.

## Summary

- The global climate is naturally variable. Anthropogenic CO<sub>2</sub> emissions add to that variability by changing the total radiative balance in the atmosphere.
- The IPCC has downplayed the role of the sun in climate change but there are Total Solar Irradiance reconstructions that imply it might have been important, and the modern record is uncertain due to an interruption in satellite coverage.
- Projections of anthropogenic emissions are combined with carbon cycle model estimates of atmospheric CO<sub>2</sub> removal to estimate future CO<sub>2</sub> concentrations and hence the radiative forcings. These are input to climate models to estimate future anthropogenic changes in the climate.
- IPCC emission scenarios envelopes have tended to exceed observed trends.
- The vast majority of academic climate “impacts” studies in recent years are based upon the extreme RCP8.5 scenario that is considered implausible; its usage as a business-as-usual scenario is misleading.
- Despite ample evidence that scenario envelopes are exaggerated, and despite criticism of this practice in the peer-reviewed literature, the IPCC’s most recent scenario set (SSP) perpetuates this malpractice.
- The global carbon cycle heavily dampens the effect of changes in local (e.g. U.S.) CO<sub>2</sub> emissions. Even global-scale emission reductions will have only small, much delayed effects.
- ~~Knowing the magnitude of CO<sub>2</sub> warming requires knowing the strength of aerosol cooling. While that is uncertain, a substantial body of recent evidence points to it being relatively weak, implying CO<sub>2</sub> warming is likewise weak. THIS IS AN ATTRIBUTION STATEMENT~~

Scaffeta, Nicola, Richard C. Willson, Jae N. Lee and Dong Wu (2019) Modeling Quiet Solar Luminosity Variability from TSI Satellite Measurements and Proxy Models during 1980–2018. *Remote Sensing* 11(21) 2569 <https://doi.org/10.3390/rs11212569>

Connolly, Roman, Willie Soon, Michael Connolly et al. (2021) How much has the Sun influenced Northern Hemisphere temperature trends? An ongoing debate *Research in Astronomy and Astrophysics* 21(6) doi: 10.1088/1674-4527/21/6/131 <https://iopscience.iop.org/article/10.1088/1674-4527/21/6/131>

Zacharias, Pia (2014) An Independent Review of Existing Total Solar Irradiance Records. *Surveys in Geophysics* 35 pp. 897—912 <https://link.springer.com/article/10.1007/s10712-014-9294-y>

Liu, Pengfei et al. (2021) “Improved estimates of preindustrial biomass burning reduce the magnitude of aerosol climate forcing in the Southern Hemisphere” *Science Advances* 7(22) May 2021 <https://doi.org/10.1126/sciadv.abc1379>

Wang, C., Soden, B. J., Yang, W., & Vecchi, G. A. (2021). Compensation between cloud feedback and aerosol-cloud interaction in CMIP6 models. *Geophysical Research Letters*, 48, e2020GL091024. <https://doi.org/10.1029/2020GL091024>

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**From:** Steven Koonin <steven.koonin@gmail.com>  
**Sent:** Friday, May 2, 2025 1:54 PM  
**To:** 'Judith Curry'; 'Roy Spencer'  
**Cc:** 'Ross McKittrick'; 'Travis Fisher'; 'John Christy'  
**Subject:** my suggested edits of 4  
**Attachments:** 4.AnthropogenicRF.Apr29 [SEK].docx

See attached. Now on to 5!

SEK

## 4 Human influences on the climate

### 4.1 Components of radiative forcing and their history

#### 4.1.1 Historical radiative forcing

A changing climate has been the norm throughout the Earth's 4.6-billion-year history. The Earth's temperature and weather patterns change naturally over timescales ranging from decades to millions of years. Natural variations in the surface climate originate in two ways. Internal climate fluctuations associated with circulations in the atmosphere and ocean produce exchanges of energy, water, and carbon between the atmosphere, oceans, land, and ice. External influences on the climate system include variations in the energy received from the sun and the effects of volcanic eruptions. Human activities influence climate through changing land use and land cover. Humans are also the composition of the atmosphere by increasing emissions of CO<sub>2</sub> and other greenhouse gases and by altering the concentrations of aerosol particles in the atmosphere.

The earth is warmed by the sunlight it absorbs and cooled by the radiative heat it emits to outer space. Averaged over Earth, each of these processes involve power flows of about 240 Watts per square meter (W/m<sup>2</sup>). When they are in balance, there are no net external causes of warming or cooling. Human (and some natural) influences on the climate alter this balance and so cause the climate to change.

Influences on the energy balance are quantified by "radiative forcing", the extent to which they disturb the warming/cooling balance; a positive forcing warms while a negative forcing cools. The IPCC's estimated history of major components of radiative forcing since 1750 is shown in the following two figures from the IPCC AR6.

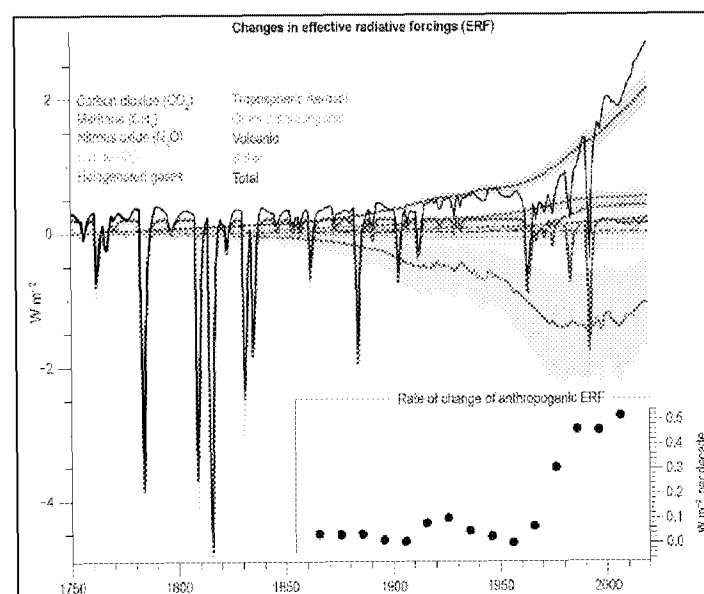


Figure 4.1.1: IPCC estimates of radiative forcing components over time. Source: <https://www.ipcc.ch/report/ar6/wg1/figures/chapter-2/figure-2-10/>

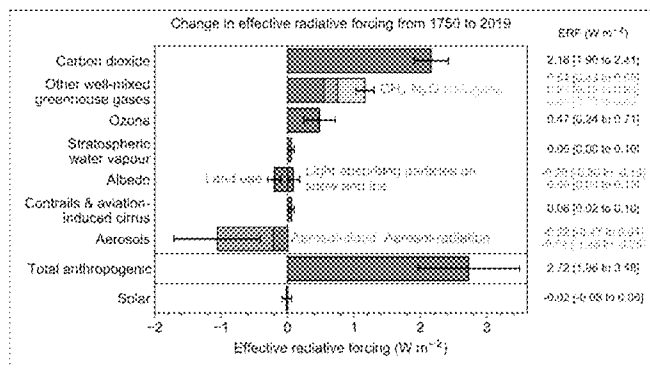


Figure 4.1.2 IPCC estimates of radiative forcing component changes from 1750 to 2019. Source: <https://www.ipcc.ch/report/ar6/wg1/figures/chapter-7/figure-7-6/>

These graphs show that the total radiative forcing is comprised of natural and anthropogenic components. Carbon dioxide is the largest human influence on the climate and the one most relevant to the effects of energy-using systems like motor vehicles. It exerts a warming influence by decreasing the cooling power of the atmosphere. Emissions of CO<sub>2</sub> are accumulating in the atmosphere, as described in the following section, so that the warming influence is increasing. Other greenhouse gases (methane, nitrous oxide, halogens, and ozone), which act similarly, currently add another 75% to CO<sub>2</sub>'s warming. Aerosols exert a cooling effect, although with large uncertainties in the way they catalyze the formation of reflective clouds. As a result, understanding of the causes of recent warming requires not just identifying the warming effects of CO<sub>2</sub>, but also the more uncertain cooling effects of sulfate aerosols.

The IPCC views the role of the sun as negligible, based on their preference for reconstructions that imply minimal solar change since preindustrial times. Connolly *et al.* (2021) reviewed sixteen different Total Solar Irradiance (TSI) reconstructions in the literature covering the 1600-2000 interval; they vary from almost no change in TSI to a relatively large upward trend. Connolly *et al.* point out that the variation in TSI reconstructions combined with variations in surface temperature reconstructions implies pairings can be found that are consistent with either no or most 20<sup>th</sup> century warming being attributable to the sun. A particularly thorny issue is the gap in the TSI data between 1989 and 1991 due to a delay in the launch of a monitor after the Space Shuttle Challenger disaster on January 28 1986, which prevented a replacement satellite from being launched in time to overlap with, and its readings to be intercalibrated with, the prior system (Zacharias 2014, Scafetta et al. 2019). The question of whether there is an upward trend

in TSI over 1978 to 2018 comes down to how the missing data in that gap are filled. That being the case it is noteworthy that Zacharias (2014) observes the solar research community has been motivated by a desire to downplay any potential role of the sun in climate change so as not to detract from arguments for greenhouse gas abatement:

A conclusive TSI time series is not only desirable from the perspective of the scientific community, but also when considering the rising interest of the public in questions related to climate change issues, thus preventing climate skeptics from taking advantage of these discrepancies within the TSI community by, e.g., putting forth a presumed solar effect as an excuse for inaction on anthropogenic warming.

(Zacharias 2014)

The other natural forcing component is largely volcanic aerosols, which exert an episodic cooling influence.

The anthropogenic forcing component was negligible before about 1900 and has increased steadily since, rising to almost 3 W/m<sup>2</sup> today. However, this is still only about 1 percent of the unperturbed radiation flows, making it a challenge to isolate the effects of anthropogenic forcing since state-of-the-art satellite estimates of global radiative energy flows are only accurate to a few W/m<sup>2</sup>. Natural sources of global energy imbalance other than volcanoes are not included in these graphs because they remain largely unknown.

#### 4.1.2 Future radiative forcing

Carbon dioxide's warming influence depends upon how much "extra" CO<sub>2</sub> accumulates in the atmosphere- i.e., its concentration. The CO<sub>2</sub> level as recorded at the Mauna Loa observatory in Hawaii is generally used as the representative global average concentration. The data are available online at <https://gml.noaa.gov/ccgg/trends/index.html>. The concentration was about 316 ppm at the start of the record in 1959 and is now about 425 ppm, a 34 percent increase.

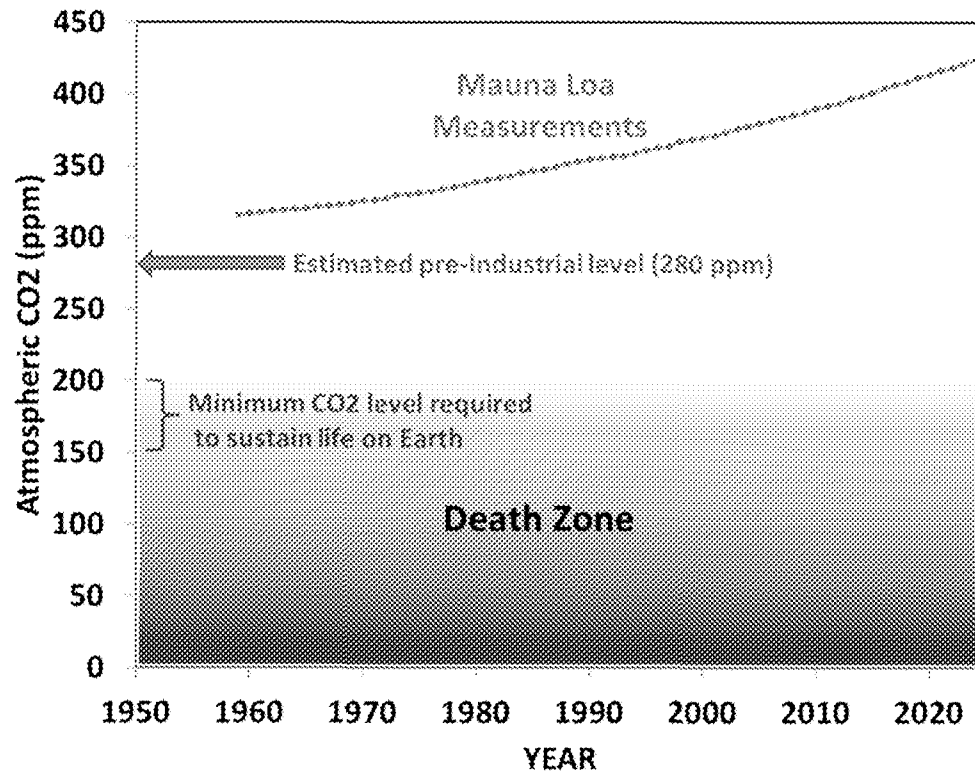


Fig. 4.1.3 Yearly average atmospheric CO<sub>2</sub> concentrations (1959-2024) measured at Mauna Loa, HI (green) compared to the estimated pre-Industrial CO<sub>2</sub> concentration of 280 ppm, and the estimated minimum levels required to sustain life on Earth (150 to 200 ppm). Need source

The annual increase in concentration is only about half of the CO<sub>2</sub> emitted because land and ocean processes absorb “excess” CO<sub>2</sub> at a rate approximately 50% of human emissions. Thus, future concentrations, and hence future human influences on the climate, depend upon two components: (1) future rates of global human CO<sub>2</sub> emissions, and (2) how fast the land and ocean remove extra CO<sub>2</sub> from the atmosphere. We discuss each of these in turn.

## 4.2 Future emission scenarios and the carbon cycle

### 4.2.1 Emission scenarios

Assessing the future dangers of GHG emissions requires assumptions about what those emissions will be. Future emissions, and hence human influences on the climate, will depend upon future



demographics, economic progress, regulation, and the energy and agricultural technologies in use. Various assumptions about each of those lead to projections of greenhouse gas emissions and concentrations, aerosol concentrations, and changes in land use, which ultimately can be combined into assumptions about anthropogenic radiative forcing.

Because of the great uncertainties about these many factors the decades to come, instead of making precise predictions of future concentrations, the IPCC has created various sets of scenarios meant to span a plausible range of possibilities for population, economy, technology, and so on. Recent versions of the scenarios are labeled by a number indicating the anthropogenic radiative forcing expected in 2100 under that scenario. Thus, a scenario labeled with a “6” corresponds to 6 W/m<sup>2</sup> of human-induced radiative forcing (warming) at the end of the century. (Recall current anthropogenic radiative forcing is about 2.7 W/m<sup>2</sup>.)

Although the IPCC does not put its emission scenarios forward as forecasts they are often treated as such. Comparisons of past scenario groups against observations shows a tendency for IPCC emission projections to overstate actual subsequent emissions. For the IPCC Third and Fourth Assessment Reports a set of emission projections from the *Special Report on Emission Scenarios* were used and hence were referred to as the SREP scenarios. McKittrick *et al.* (2012) showed that, when converted to per capita terms, the SREP scenario distribution was skewed upwards and incompatible with observed trends. McKittrick and Wood (2013) further showed that global energy market dynamics constrained global per capita CO<sub>2</sub> emissions to an extent not reflected in IPCC scenarios. The bias of the SRES scenarios was confirmed by the later analysis in Hausfather *et al.* (2019) who showed that observed atmospheric CO<sub>2</sub> concentrations tracked the low end of the SRES range.

For the Fifth Assessment Report the IPCC developed a new set of scenarios called the Representative Concentration Pathways (RCP). These were identified by a number representing the increase in forcing and were thus called RCP2.6, RCP4.5, RCP6.0 and RCP8.5. RCP2.6 (implying a radiative forcing in 2100 of 2.6 W/m<sup>2</sup>) projects a GHG concentration pathway leading to warming well below 2 C. At the other end of the scale RCP8.5 is an extreme outcome implying nearly 5 C warming just in this century.

RCP8.5 came to be referred to as the no-policy baseline, or “business-as-usual” scenario in both the academic literature and popular media. It was therefore used to generate the reference outcome supposedly representing the 21<sup>st</sup> century world in the absence of emission reduction policies. But RCP8.5 was intended as a low-probability high emissions scenario and its usage as a business-as-usual baseline has been criticized as grossly misleading.<sup>1</sup> Hausfather and Peters (2020) writing in a commentary in *Nature* magazine, pointed out that RCP8.5 was developed as

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<sup>1</sup> This extreme scenario is useful for modelers, since a large forcing generates a large response (warming) making it easier to assess a model’s sensitivity. But that’s very different than claiming it is a plausible future.

an extreme worst-case, and its misuse as a “business as usual” baseline has resulted in a large number of misleading studies and media reporting:

RCP8.5 was intended to explore an unlikely high-risk future. But it has been widely used by some experts, policymakers and the media as something else entirely: as a likely ‘business as usual’ outcome. A sizeable portion of the literature on climate impacts refers to RCP8.5 as business as usual, implying that it is probable in the absence of stringent climate mitigation. The media then often amplifies this message, sometimes without communicating the nuances. This results in further confusion regarding probable emissions outcomes, because many climate researchers are not familiar with the details of these scenarios in the energy-modelling literature.

(Hausfather and Peters 2020)

The implausibility of the RCP8.5 scenario was examined by Burgess *et al.* (2021). They noted that RCP8.5 has already diverged from observed energy use trends, and the near future trends diverge sharply from those of the International Energy Agency (IEA) which provides market-based projections of energy use for coming decades. IEA trends are based on plausible extrapolations of current economic and demographic trends, and the results run below the entire envelope of RCP projections, implying not only that RCP8.5 is dubious, but even lower emission scenarios are looking unlikely. Burgess *et al.* comment (p. 8):

Beyond 2040, if the trends anticipated by energy agency forecasts continue, carbon intensity will continue diverging from AR5 and SSP baselines—especially from higher-emission scenarios such as RCP8.5, due to the assumptions about fossil-fuel expansion in these scenarios that are increasingly implausible.

Widespread use of RCP8.5 has created an alarmist bias in the climate impacts literature. The extent of this problem was confirmed in a literature analysis by Pielke Jr. and Ritchie (2020). They found (p. 32) that some 16,800 scientific papers published between 2010 and 2020 used the RCP8.5 scenario, with about 4,500 of the articles (p. 16) linking RCP8.5 with the concept of “business-as-usual”. Their analysis showed how RCP8.5 was misused not only by individual researchers, but also by influential science agencies like the IPCC and the US National Climate Assessment (USNCA), which has directly led to misleading coverage in prominent media outlets. They offer the following example (p. 30):

The USNCA employed RCP8.5 as a baseline scenario, despite warning against such use, and compared it to RCP4.5 throughout its report to generate quantitative economic estimates of the benefits of mitigation. In a front-page story, the *New York Times* promoted the report’s misuse of RCP8.5 as a baseline scenario:

“A major scientific report issued by 13 federal agencies on Friday presents the starkest warnings to date of the consequences of climate change for the United States, predicting that if significant steps are not taken to rein in global warming, the damage will knock as much as 10 percent off the size of the American economy by century’s end.”

Pielke and Ritchie (2020) reported new studies using RCP8.5 were appearing in the literature at a rate of about 20 per day, with about two per day specifically linking RCP8.5 and “business as usual.” They conclude (p. 34) that the climate research community has spent a decade “committing scientific resources to science fiction” (emphasis added):

“Derived estimates from RCP8.5 as “business as usual” such as future climate impacts, the impacts avoided from mitigation and the cost effectiveness and benefits of mitigation have no real-world meaning... **The scientific literature has become imbalanced in an apocalyptic direction.**

(Pielke Jr. and Ritchie p. 34)

The IPCC later converted the RCP scenarios to the “Shared Socioeconomic Pathway” or SSP scenarios, but these have continued the pattern of bias shown with the RCP and SRES scenarios. Figure 3.1.4 was generated using the Resources for the Future Global Energy Outlook tool (RFF 2025). The black line shows total global observed CO<sub>2</sub> emissions compiled by the International Energy Agency (IEA). The solid green line is the emission trajectory developed by BP Energy taking account of current emission control policies and global energy use outlooks. It overlaps a solid black line which represents the emission projection from the IEA also taking account of energy use projections and current policies. The dashed lines show the range of IPCC SSP policies. As of 2023 global CO<sub>2</sub> emissions have been tracking well below the SSP scenarios especially the two highest ones (SSP5-8.5 and SSP3-7.0).

Carbon dioxide emissions (Million metric tons), by Outlooks & Scenarios. Filtered by Region: World; Fuel: All; Outlook: 2023 Shell (Sky 2050).

Source: RFF Global Energy Outlook at [www.rff.org/geo](http://www.rff.org/geo)

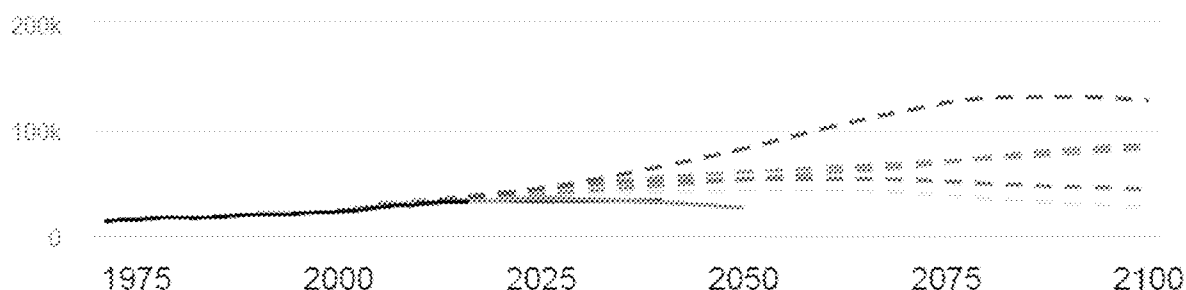


Figure 4.2.1. Observed and projected CO<sub>2</sub> emissions. Source: RFF (2025).

#### 4.2.2 The carbon cycle relating emissions and concentrations

Global carbon cycle models relate concentrations to emissions using estimates of various land and ocean processes that remove CO<sub>2</sub> from, and emit CO<sub>2</sub> into, the atmosphere. Our understanding of these processes was reviewed by Crisp et al. (2021). The natural fluxes of CO<sub>2</sub> in and out of the Earth's surface are very large, many times anthropogenic emissions, but those CO<sub>2</sub> sources and sinks were assumed to be in approximate balance in pre-Industrial times, as evidenced by relatively constant levels of atmospheric CO<sub>2</sub> in centuries past derived from air bubbles in ice cores. This is one of several reasons why increasing atmospheric CO<sub>2</sub> levels are believed to be dominated by anthropogenic sources.

Specifically, fossil fuel burning (and to a lesser extent land use [biomass burning] and cement production) has led to steadily increasing CO<sub>2</sub> levels in the atmosphere, as shown in Fig. 1.2.1. CO<sub>2</sub> emissions from fossil fuel burning is a small fraction of the natural carbon cycle components. About 44,000 Gigatonnes of carbon-equivalent (GtC) are stored in the atmosphere and oceans, mostly in the form of CO<sub>2</sub>. (Ciais et al. 2013). Between 150 and 200 GtC are released naturally each year through oceanic outgassing and land-based processes like plant decay and animal respiration. A variable but roughly equivalent amount is absorbed each year by the land and oceans, with a small net loss from the atmosphere because the formation of deep ocean sediment sequesters some carbon permanently. Global fossil fuel consumption and cement manufacture released about 10.3 GtC in 2023, up from 6.2 GtC in 1990 (Ritchie et al.

2024). Of this, about half is naturally sequestered through plant growth and oceanic uptake while the remainder, about half, adds to the atmospheric stock (Ciais et al. 2013).

As noted, each year natural processes remove a net amount of CO<sub>2</sub> equivalent to about 50% of global emissions. Thus, anthropogenic CO<sub>2</sub> emissions average twice what is required to explain the atmospheric rise in CO<sub>2</sub> concentration. The near-constancy of that 50% fraction (the “airborne fraction”) also means that the more CO<sub>2</sub> humanity produces, the faster Nature removes it from the atmosphere. That 50% fraction changes somewhat from year to year due to natural carbon cycle imbalances from El Nino, La Nina, and varying weather patterns. There was also a substantial additional reduction in atmospheric CO<sub>2</sub> after the 1991 eruption of Mt. Pinatubo, a curious result that has yet to be explained (Angert et al., 2004).

The main processes which remove excess CO<sub>2</sub> from the atmosphere are increased production of land vegetation (especially at high latitudes), some increase in the sequestering of carbon in soils, and uptake of CO<sub>2</sub> by the ocean due to the increasing partial pressure of atmospheric CO<sub>2</sub> over that of CO<sub>2</sub> dissolved in the ocean. All twenty land carbon cycle models tracked by the Global Carbon Project (Friedlingstein et al., 2024) show land processes have been removing excess CO<sub>2</sub> at an increasing rate since 1959. This is consistent with a “global greening” phenomenon observed by satellites since monitoring of global greenness began in the 1982. This greening has been traced to CO<sub>2</sub> fertilization and greater drought tolerance of plants exposed to elevated CO<sub>2</sub> levels. While there had been some uncertainty whether a greening trend continued beyond 2000, the most recent research (Chen et al., 2023) has shown continued greening, with even some slight acceleration since 2000. Global greening is discussed further in Section 3.1.

While land vegetation has been responding positively to more atmospheric CO<sub>2</sub>, uptake of extra CO<sub>2</sub> by ocean biological processes remains too uncertain to be reliably measured. Our current understanding of these and many more carbon cycle processes was reviewed by Crisp et al. (2021).

Public policy can only change the rate of emissions, not the concentration in the atmosphere. For criteria air contaminants the rate and concentration are closely connected because the lifetime is short and the concentration is small. When emissions are reduced the local pollution concentration drops rapidly, usually on a time scale of a few days. Not so with the global average CO<sub>2</sub> concentration since global carbon cycle is vast and slow. A change in local emissions today will only have a very small global effect, and only after a long time lag. After a pulse (release) of CO<sub>2</sub> emissions to the atmosphere only about 40 percent ( $\pm 15\%$ ) of the extra CO<sub>2</sub> will have been sequestered after twenty years. After a thousand years about 75 percent ( $\pm 10\%$ ) will have been sequestered, and the remainder will gradually be removed over the ensuing tens of thousands of years (Ciais et al. 2013, pp. 472-473). Consequently US CO<sub>2</sub> emission reductions will take decades or centuries to lead to a reduction in the global CO<sub>2</sub> concentration.

To reduce the atmospheric stock of CO<sub>2</sub>, assuming the entire increase is anthropogenic, would require emissions to fall below the natural sequestration rate. Since that rate has been averaging about 50% of emissions, a reduction of global emissions by 50% would (at least temporarily) halt the rise in atmospheric CO<sub>2</sub>. The 1997 Kyoto Protocol proposed to cap industrial nations' CO<sub>2</sub> emissions at a modest five percent below 1990 levels by the year 2012. Even though this policy ended up too costly for most nations to implement, full compliance would not have substantially reduced atmospheric CO<sub>2</sub> levels. It would only have slightly slowed CO<sub>2</sub> growth, reaching the projected 2100 level in 2105 instead (Wigley 1998). Similarly, Lomborg (2016) used the widely-used MAGICC climate model and showed that full compliance with the Paris Accord would not stop warming, it would only prevent about 0.1C warming and delay hitting the baseline year 2100 temperature levels by about a decade.

Thus, in contrast with conventional air pollution control, local actions yield extremely small local effects, and only after a long time lag. The practice of referring to unilateral US reductions as “combatting climate change” or “taking action on climate” reflects a profound misunderstanding of the scale of the issue. The scale problem is compounded by recognizing that US motor vehicles account only for about 4 percent of global CO<sub>2</sub> emissions so even a fifty percent reduction in those emissions would have a vanishingly small effect on the global climate.

#### 4.3 Aerosols and the uncertainties associated with them

The climate's sensitivity to CO<sub>2</sub> (as quantified by ECS, the Equilibrium Climate Sensitivity<sup>2</sup>) is uncertain in part because the anthropogenic radiative forcing is uncertain because the net forcing results from (at least) two counteracting components: warming from GHG's and cooling from aerosols. The observed warming can therefore be made to be consistent with a wide range of pairs of these forces. In the following schematic, the net warming represented by the red arrow could be due to the High GHG warming/strong aerosol cooling pair, or the Low GHG warming/weak aerosol cooling pair, or something in between.

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<sup>2</sup> ECS is formally defined as the increase in equilibrium global average surface temperature resulting from a doubling of the atmospheric CO<sub>2</sub> concentration above its pre-industrial value of 280 ppm. Estimates of ECS are reviewed in Section XX.

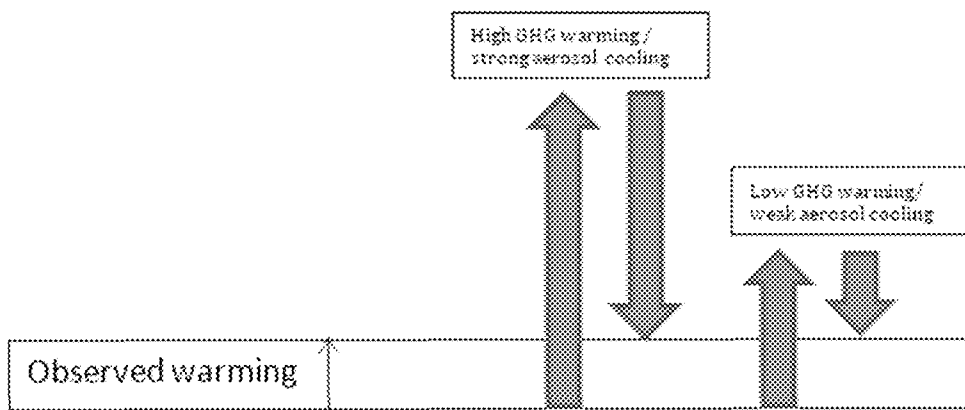


Figure 4.3.1: High and low climate sensitivity to GHGs can be reconciled with the same warming by assuming an offsetting aerosol cooling effect.

Research on the strength of aerosol cooling is therefore central to more precise ECS estimates. Lewis and Curry (2018) note that after the IPCC AR5 was published in 2013, eleven studies appeared in the scientific literature all finding that aerosol cooling was weaker than had previously been conjectured. Combining the updated aerosol estimates with greenhouse gas, ocean heat uptake and atmospheric warming data from the IPCC and applying standard empirical methods, Lewis and Curry (2018) estimated the best-guess ECS to be 1.66°C with a 95 percent uncertainty range of 1.15 °C – 2.7°C. They concluded that based on the ECS values derived from most IPCC climate models were incompatible with observed data.

There has been further evidence of lower aerosol cooling (implying lower ECS) such as Liu et al. (2021). These authors tested the hypothesis that aerosols from wildfires has increased since before the 20<sup>th</sup> century which, if true, would mean there had to have been relatively strong CO<sub>2</sub> warming over that period offsetting the aerosol cooling. They examined soot layers in ice cores extracted from Antarctica and South America and determined that wildfire activity prior to the 20<sup>th</sup> century was higher than previously believed. Instead of wildfire activity rising steadily from the 1700s to the present, it was high all the time, thus contradicting the hypothesized aerosol cooling trend in the Southern Hemisphere during the 20<sup>th</sup> century. They pointed out how this finding relates to the climate sensitivity issue:

Accurate estimates of aerosol radiative forcing are also crucial for better understanding the transient climate response (TCR) and equilibrium climate sensitivity (ECS) to increasing CO<sub>2</sub> and more accurate projection of future climate change. The negative aerosol radiative forcing can, in part, cancel out the positive forcing of increasing greenhouse gases and contribute to the uncertainty of total radiative forcing. An overly

large aerosol cooling implies that models might overestimate TCR and ECS to reproduce historical temperature response. A recent study using one of the latest-generation CMIP6 climate models (E3SM) suggested that reducing both the magnitudes of negative aerosol radiative forcing and climate sensitivity yields a better agreement with the observed historical record of the surface temperature.

(Liu et al. 2021)

Liu told the UK Daily Mail<sup>3</sup>

Climate scientists have known that the most recent generation of climate models have been over-estimating surface temperature sensitivity to greenhouse gasses, but we haven't known why or by how much. This research offers a possible explanation.

More evidence pointing to weak aerosol cooling was reported by Wang *et al.* (2021). They noted that the strength of aerosol cooling is partly mediated by cloud behavior and differs between the North and South Hemispheres because of the different density of aerosol emissions. This allowed them to construct another test of climate model validity, which came out in favor of low ECS models. In their words:

Since anthropogenic aerosols primarily concentrate in the Northern Hemisphere, strong aerosol-cloud interaction models produce an interhemispheric asymmetric warming. We show that the observed warming asymmetry during the mid to late 20th century is more consistent with low ECS (weak aerosol indirect effect) models.

Wang et al. (2021)

To summarize, quantifying warming due to CO<sub>2</sub> requires understanding the strength of aerosol cooling. While that latter is uncertain a substantial body of recent evidence points to it being relatively weak, implying that CO<sub>2</sub> warming is likewise weak.

Summary

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<sup>3</sup> Available online at <https://www.dailymail.co.uk/sciencetech/article-9629919/Climate-change-warming-effect-greenhouse-gases-overestimated-ice-core-study-suggests.html>



- The global climate is naturally variable. Anthropogenic CO<sub>2</sub> emissions add to that variability by changing the total radiative balance in the atmosphere.
- The IPCC has downplayed the role of the sun in climate change but there are Total Solar Irradiance reconstructions that imply it might have been important, and the modern record is uncertain due to an interruption in satellite coverage.
- Projections of anthropogenic emissions are combined with carbon cycle model estimates of atmospheric CO<sub>2</sub> removal to estimate future CO<sub>2</sub> concentrations and hence the radiative forcings. These are input to climate models to estimate future anthropogenic changes in the climate.
- IPCC emission scenarios envelopes have tended to exceed observed trends.
- The vast majority of academic climate “impacts” studies in recent years are based upon the extreme RCP8.5 scenario that is considered implausible; its usage as a business-as-usual scenario is misleading.
- Despite ample evidence that scenario envelopes are exaggerated, and despite criticism of this practice in the peer-reviewed literature, the IPCC’s most recent scenario set (SSP) perpetuates this malpractice.
- The global carbon cycle heavily dampens the effect of changes in local (e.g. U.S.) CO<sub>2</sub> emissions. Even global-scale emission reductions will have only small, much delayed effects.
- Knowing the magnitude of CO<sub>2</sub> warming requires knowing the strength of aerosol cooling. While that is uncertain, a substantial body of recent evidence points to it being relatively weak, implying CO<sub>2</sub> warming is likewise weak.

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Connolly, Roman, Willie Soon, Michael Connolly et al. (2021) How much has the Sun influenced Northern Hemisphere temperature trends? An ongoing debate *Research in Astronomy and Astrophysics* 21(6) doi: 10.1088/1674-4527/21/6/131 <https://iopscience.iop.org/article/10.1088/1674-4527/21/6/131>

Zacharias, Pia (2014) An Independent Review of Existing Total Solar Irradiance Records. *Surveys in Geophysics* 35 pp. 897—912 <https://link.springer.com/article/10.1007/s10712-014-9294-y>

Liu, Pengfei et al. (2021) “Improved estimates of preindustrial biomass burning reduce the magnitude of aerosol climate forcing in the Southern Hemisphere” *Science Advances* 7(22) May 2021 <https://doi.org/10.1126/sciadv.abc1379>

Wang, C., Soden, B. J., Yang, W., & Vecchi, G. A. (2021). Compensation between cloud feedback and aerosol-cloud interaction in CMIP6 models. *Geophysical Research Letters*, 48, e2020GL091024. <https://doi.org/10.1029/2020GL091024>

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**From:** John Christy <climateman60@gmail.com>  
**Sent:** Monday, May 12, 2025 2:12 PM  
**To:** Steve Koonin  
**Cc:** Ross McKittrick; Judith Curry; Roy W. Spencer; Travis Fisher  
**Subject:** Re: my edits of 1,2,3

Agreed.

John Christy  
Director, Earth System Science Center  
Professor, Atmos and Earth Science  
Alabama State Climatologist  
The University of Alabama in Huntsville  
climateman60@gmail.com

On May 12, 2025, at 10:29 AM, Steven Koonin <steven.koonin@gmail.com> wrote:

Looks good.

SEK

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**From:** Ross McKittrick <ross.mckittrick@gmail.com>  
**Sent:** Monday, May 12, 2025 10:31 AM  
**To:** Judith Curry <curry.judith@gmail.com>  
**Cc:** Steven Koonin <steven.koonin@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; John Christy <climateman60@gmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>  
**Subject:** Re: my edits of 1,2,3

I made a few edits as noted in italics at the top. The Clements article makes quite the point.

On Mon, May 12, 2025 at 10:18 AM Judith Curry <[curry.judith@gmail.com](mailto:curry.judith@gmail.com)> wrote:  
I'm good with SK's versions of 1-3

On Sun, May 11, 2025 at 6:10 PM Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)> wrote:

I've been going through the chapters systematically. Here's the first few (can't post to Dropbox). More in the next few days.

Steve Koonin

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**From:** Steven Koonin <steven.koonin@gmail.com>  
**Sent:** Monday, May 12, 2025 11:29 AM  
**To:** 'Ross McKittrick'; 'Judith Curry'  
**Cc:** 'Roy W. Spencer'; 'John Christy'; 'Travis Fisher'  
**Subject:** RE: my edits of 1,2,3

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SEK

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**To:** Judith Curry [curry.judith@gmail.com]  
**CC:** Steven Koonin [steven.koonin@gmail.com]; Roy W. Spencer [roywspencer@hotmail.com]; John Christy [climatemanager60@gmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]  
**Subject:** Re: my edits of 1,2,3  
**Attachments:** 3 Alkaline Oceans.May11[SEK][RM].docx

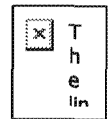
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### 3. Increasing CO<sub>2</sub> and the Alkaline Oceans

*{Ross May 12 edit notes: added citation for pH figure. Moved paleo paragraph closer to start. It was decided to reword various paragraphs to remove passive tense where possible. Expanded discussion of Clements et al – quite an important article – and updated the citation to the published version. Expanded the concluding paragraph}*

A neutral aqueous solution has a pH of 7.0, while one with pH greater than 7.0 is basic and with pH less than 7.0 is acidic. The modern-day global average pH of sea water is estimated to be 8.04 (Copernicus Marine Service 2025), down from an estimated value of 8.2 in pre-Industrial times (Gattuso and Hansson, 2011). As CO<sub>2</sub> concentrations in the atmosphere increase, more is absorbed by the oceans, which decreases alkalinity. Depending upon the buffering capacity of the oceans, the oceans are expected to become somewhat less alkaline over time, consistent with the observed decrease in pH.

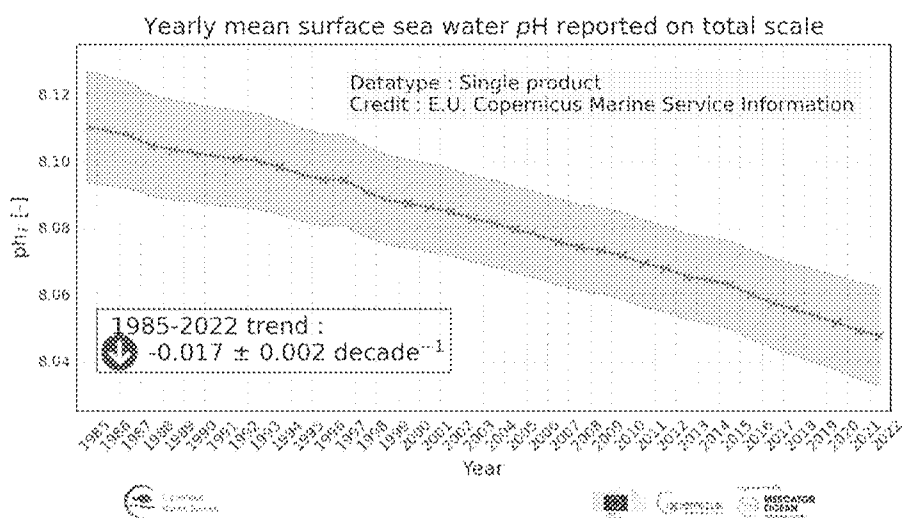


Figure 3.1: Ocean pH 1985 – 2022. Source: Copernicus Marine Service 2025

While this process is often called “ocean acidification”, it is a misnomer because the oceans are not expected to become acidic; “ocean neutralization” would be more accurate. Even if the water were to turn acidic, it is believed that life in the oceans evolved when the oceans were mildly acidic with pH 6.5 - to 7.0 (Krissansen-Totton et al., 2018). On the time scale of thousands of years, boron isotope proxy measurements of pH show that ocean pH was around 7.4 or 7.5 during the last glaciation (up to about 20,000 years ago) increasing to present-day values as the world warmed during deglaciation (Rae et al., 2018). Thus, there appears to be considerable resilience of ocean biota to natural long-term changes in ocean pH since marine organisms are exposed to wide ranges in pH anyway.

There are concerns that a decreasing pH of sea water will reduce the calcification rate of coral reefs. But coral reefs already endure large swings in pH, partly due to daily photosynthetic activity in the reef; measured pH values range from 9.4 during the day to 7.5 at night (Revelle and Fairbridge, 1957). De’ath

et al. (2009) reported that a portion of Australia's Great Barrier Reef (GBR, the world's largest coral reef ecosystem) had experienced a 14% decline in calcification since 1990. This was tentatively attributed to increasing water temperature and decreasing pH. But Ridd et al. (2013) showed that report to have resulted from a biased data analysis which, when corrected, showed no change in calcification rates. Nevertheless, the alarm produced by the original paper has persisted as evidenced by the large number of published citations (541) received by the original study compared to only 11 citations for the correction (as of 30 April 2025).

The most recent annual summary of GBR conditions from the Australian Institute of Marine Science indicates a strong rebound has occurred in coral production (AIMS, 2022). Much of the decline in the GBR before 2011 turned out to be due to intense tropical cyclone activity (Beeden et al., 2015) as well as a string of marine heatwaves, agricultural runoff and invasive species (Woods Hole 2023). Given the reported declines in GBR calcification between 1990 and 2009 and the continued increase in atmospheric CO<sub>2</sub> levels the rebound has come as a surprise to some observers.

It is being increasingly recognized that publication bias (alarming ocean acidification results preferred by high-impact research publications) exaggerates the impacts of declining ocean pH. An ICES Journal of Marine Science Special Issue addressed this problem with an article entitled, *Towards a Broader Perspective on Ocean Acidification Research*. In the Introduction to that Special Issue, H. I. Browman stated, "As is true across all of science, studies that report no effect of ocean acidification are typically more difficult to publish." (Browman, 2016)

Similarly, a meta-analysis (Clements et al., 2021) of the negative effects of ocean acidification on reef fish behavior found what they called a "decline effect": initially dramatic conclusions published in the prominent journals showing apparently large reported effects of acidification tended to be followed up by subsequent studies on larger sample sizes yielding much smaller and typically non-existent effects. They call for their colleagues to improve research practices to prevent the "decline effect" from persisting:

[The] vast majority of studies with large effect sizes in this field tend to be characterized by low sample sizes, yet are published in high-impact journals and have a disproportionate influence on the field in terms of citations. We contend that ocean acidification has a negligible direct impact on fish behavior, and we advocate for improved approaches to minimize the potential for a decline effect in future avenues of research.

Clements et al. (2022)

In conclusion, much of the public discussion of the effects of ocean "acidification" on marine biota has been one-sided and exaggerated. Ocean life is complex and much of it evolved when the oceans were acidic relative to the present. There is a tendency for studies reporting dramatic effects on things like coral cover and fish behavior to get published in high-impact journals and receive widespread press coverage, whereas the subsequent research rebutting those findings tend to receive little attention.



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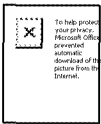
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**Subject:** Re: my edits of 1,2,3

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**From:** Ross McKittrick <ross.mckittrick@gmail.com>  
**Sent:** Sunday, May 11, 2025 11:15 PM  
**To:** Steven Koonin  
**Cc:** Judith Curry; Roy W. Spencer; John Christy; Travis Fisher  
**Subject:** Re: my edits of 1,2,3

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**From:** Steven Koonin [steven.koonin@gmail.com]  
**Sent:** 5/12/2025 1:09:54 AM  
**To:** 'Ross McKittrick' [ross.mckittrick@gmail.com]  
**CC:** 'Judith Curry' [curry.judith@gmail.com]; 'Roy W. Spencer' [roywspencer@hotmail.com]; 'John Christy' [climateman60@gmail.com]; 'Travis Fisher' [travis.scott.fisher@gmail.com]  
**Subject:** my edits of 1,2,3  
**Attachments:** 1 CO2.v.CACs.May11[SEK].docx; 2 CO2 and greening.May11.[RM][JC][RM][SEK].docx; 3 Alkaline Oceans.May11[SEK].docx

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Steve Koonin

## 1 Carbon dioxide as pollutant

In 2007, the Supreme Court ruled that GHGs (CO<sub>2</sub> among them) were “pollutants” subject to regulation under that Clean Air Act. That framework defines six types of so-called Criteria Air Contaminants (EPA, undated): particulate matter, ground-level ozone, Sulfur Dioxide, Nitrogen Dioxide, Lead and carbon monoxide (CO).

While the definition of “pollutant” is ultimately a legal one, there are important scientific distinctions between CO<sub>2</sub> and the Criteria Air Contaminants. The latter are subject to regulatory control because they cause local problems depending on concentrations that include nuisances (odor, visibility), damage to plants, and, at high enough exposure levels, toxicological effects in humans. In contrast, CO<sub>2</sub> is odorless, does not affect visibility and has no toxicological effects at ambient levels. It is a naturally-occurring part of the atmosphere and a key component of human and plant respiration. CO<sub>2</sub> is essential for plant photosynthesis and higher levels are generally considered beneficial for vegetation. In these aspects, it is similar to water.

Ambient outdoor air today contains about 420 parts per million (ppm) CO<sub>2</sub>, increasing at about 2 ppm per year. The US Occupational Safety and Health Administration issues guidelines for indoor workplaces in which elevated CO<sub>2</sub> might be encountered, such as where dry ice is used. The Permissible Exposure Limit is 5,000 ppm over 8 hours (OSHA 2024). Allen *et al.* (2015) reported evidence of diminished performance on some cognitive tasks among workers in office cubicles when exposed to CO<sub>2</sub> levels above 1,000-1,500 ppm. These levels are far larger than any plausible ambient outdoor value through the end of the 22<sup>nd</sup> century.

The growing amount of CO<sub>2</sub> in the atmosphere directly influences the earth system by promoting plant growth (global greening), thereby enhancing agricultural yields, and also by neutralizing ocean alkalinity. But the primary concern about CO<sub>2</sub> is its role as a greenhouse gas (GHG), that alters the earth’s energy balance. How the climate will respond to that influence is a complex question that will occupy much of this report.

US Environmental Protection Agency (Undated) Criteria Air Pollutants. <https://www.epa.gov/criteria-air-pollutants> accessed April 29 2025.

US Occupational Health and Safety Administration (2024) “OSHA Occupational Chemical Database: Carbon Dioxide” <https://www.osha.gov/chemicaldata/183>

Allen, Joseph G, Piers MacNaughton, Usha Satish, Suresh Santanam, Jose Vallarino and John D.S. Spengler (2015) Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation, and Volatile Organic Compound Exposures in Office Workers: A Controlled Exposure Study of Green and Conventional Office Environments. *Environmental Health Perspectives* 124(6) pp. 805-812 <https://doi.org/10.1289/ehp.1510037>

## 2 CO<sub>2</sub> fertilization and global greening

The growing CO<sub>2</sub> concentration in the atmosphere has the important positive effect of promoting plant growth by enhancing photosynthesis and improving water use efficiency. That is evident in the “global greening” phenomenon discussed below, as well as in the improving agricultural yields discussed in Section XX.

### 2.1 CO<sub>2</sub> and global greening

“Greening” refers to an increase in the fraction of the Earth’s surface covered by plants. It can be quantified by the “Leaf Area Index” (LAI) measured by satellite. Many studies over the past decade have confirmed a global greening pattern (increase in LAI) attributable to rising CO<sub>2</sub> levels. Zhu *et al.* (2016) was one of the first studies to report that global greening was detectable using satellite sensors. From 1982 to 2011 they detected greening over 25-50% of the Earth versus “browning” over only 4%, and attributed 70% of the greening to rising CO<sub>2</sub> levels (see Figure 2.3).

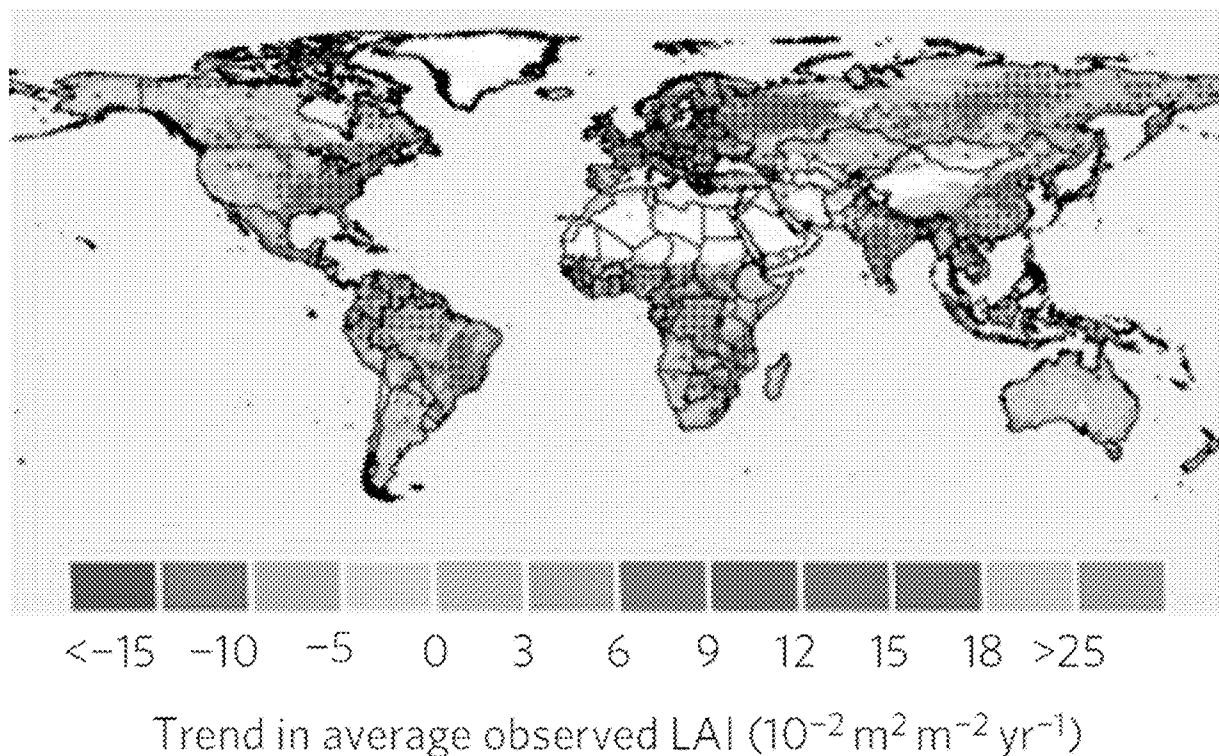


Figure 2.1.1: Trends in average Leaf Area Index (LAI). Source: Zhu et al. 2016 Figure 3.

Zheng (2017) confirmed the pattern, noting that greening over thirty years had added 8% to global leaf area and that greening was mitigating warming. Greening has been observed globally but Chen et al. (2019) noted that China and India were exploiting it though land management changes. Thus while China accounts for only 6.6% of global vegetated area it accounts for 25% of global net increase in LAI. Piao et al. (2020) noted that greening was even observable in the Arctic.

While plant models predict increases in photosynthesis in response to rising CO<sub>2</sub>, Haverd et al. (2020) reported a CO<sub>2</sub> fertilization rate nearly double what models had predicted. That is, CO<sub>2</sub> fertilization

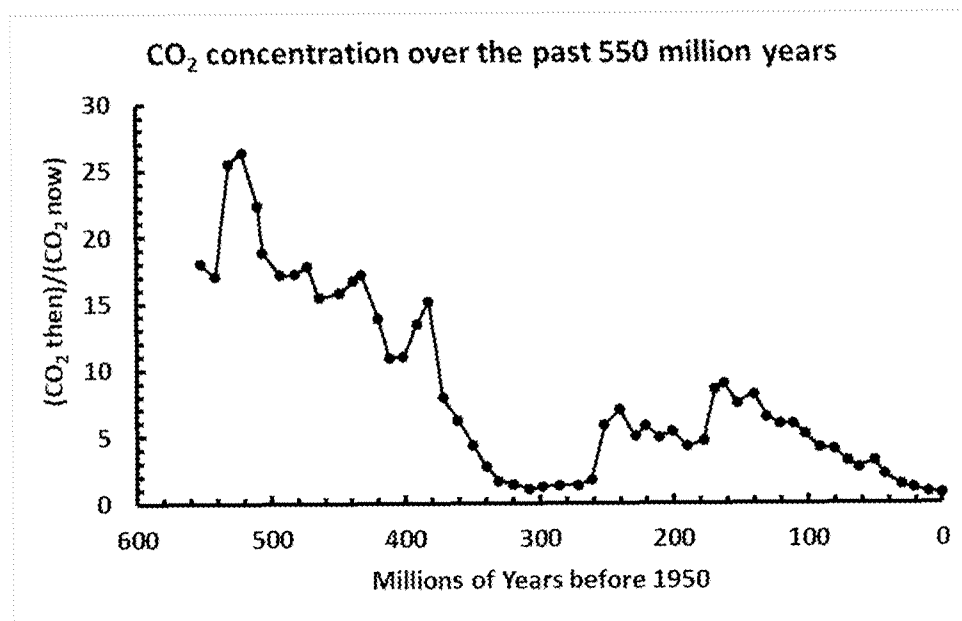
had driven an increase in observed global photosynthesis by 30% since 1900, versus 17% predicted by plant models. This indicates that global models of the socioeconomic impacts of rising CO<sub>2</sub> have likely understated the benefits to crops and agriculture. The connection between CO<sub>2</sub> fertilization and climate policy will be discussed in Chapter XX.

Finally, Chen et al. surveyed claims that greening had slowed since 2000 due to drought stress. They found instead that faulty satellite sensors were the cause and that the corrected data showed accelerated greening over 55% of the globe while browning was accelerating over only 7%. In other words, the greening trend continued with no evidence of slowdown, and CO<sub>2</sub> fertilization remained the dominant driver

## 2.2 Photosynthesis and CO<sub>2</sub> levels

Plants build biomass through *photosynthesis*, a process that converts carbon dioxide, water, and light into sugar. The plant enzyme responsible for photosynthesis is called Ribulose-1,5-bisphosphate-carboxylase/oxygenase or “Rubisco”. Photosynthesis is initiated when CO<sub>2</sub> is available at the surface of the RuBisCo enzyme where it is converted to a molecule with 3 carbon atoms and thereafter incorporated into plant mass. This is referred to as the “C3” process.

Rubisco is estimated to have evolved about 3 billion years ago. Over geological time the Earth’s atmospheric CO<sub>2</sub> levels were usually much higher than they are today, as shown in the following figure.



About 400 million years ago CO<sub>2</sub> levels were an estimated 2,000-4,000 ppm and were at or above 1,000 ppm for much of the interval from 200 to 50 million years ago (Berner 2006, Judd et al. 2024). Over the past 35 million years the level of atmospheric CO<sub>2</sub> has been steadily declining. During glaciations levels have fallen as low as 170 ppm (Gerhart and Ward 2010).

In response to low-CO<sub>2</sub> conditions some plants evolved another photosynthetic pathway called C4, in which CO<sub>2</sub> is concentrated in the vicinity of Rubisco allowing for the C3 process to function more efficiently. For agricultural purposes the plant categories are:

- C3: rice, wheat, soybeans and most other crops
- C4: maize (corn), sugar cane, millet, sorghum

Had atmospheric CO<sub>2</sub> levels continued declining, plant growth rates would have declined and eventually ceased. Below 180 ppm many C3 species experience growth rate reductions on the order of 40-60% compared to their growth rates at 350 ppm (Gerhart and Ward 2010). C3 plants have been observed under experimental conditions to stop growing altogether at levels between 60—140 ppm CO<sub>2</sub>. Some C4 plants are still able to grow at levels even as low as 10 ppm, albeit very slowly (Gerhart and Ward 2010).

Currently, CO<sub>2</sub> levels are about 420 ppm, up from 280 ppm in the early 1800s. The positive response of plants to extra CO<sub>2</sub> is illustrated in Figure 1 which is reproduced from Gerhart and Ward (2010). It shows the growth effect of CO<sub>2</sub> on Velvetleaf (*Abutilon theophrasti*) seedlings over 14 days under controlled conditions where only the CO<sub>2</sub> exposure is varied. The gains exhibited from increasing CO<sub>2</sub> from 150 ppm to 350 ppm continue under a further doubling to 700 ppm.



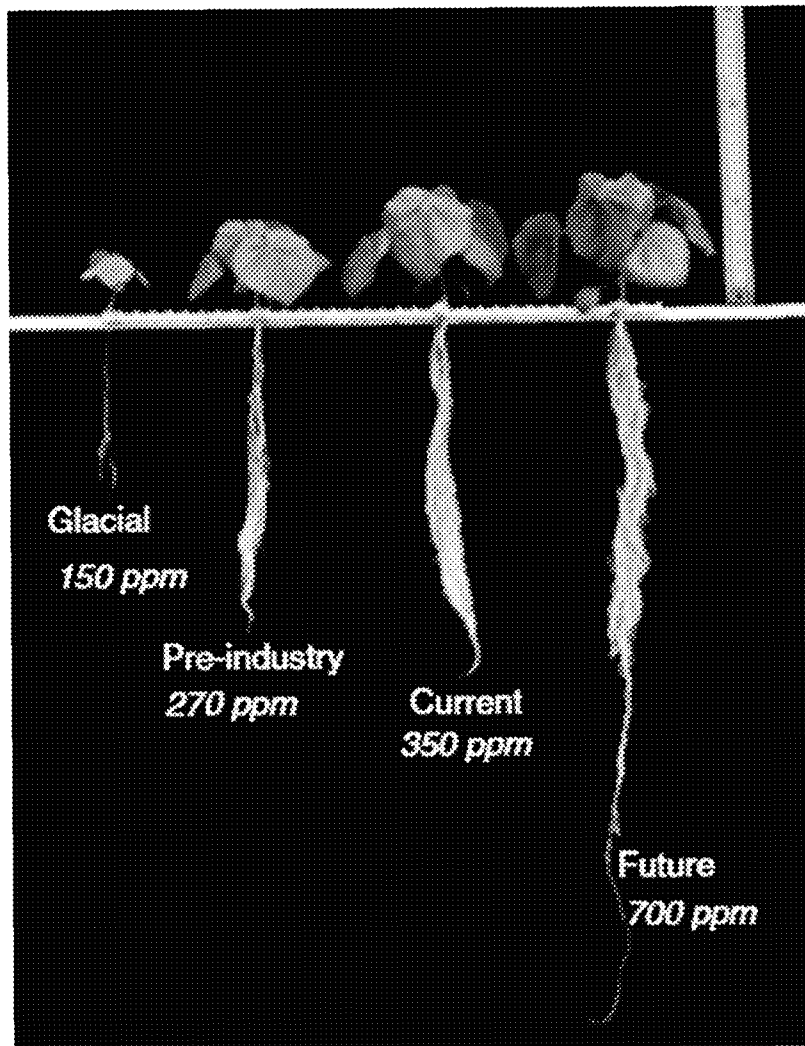


Figure 2.2.1: growth of *Abutilon theophrasti* after 14 days under identical conditions but for the indicated variations in CO<sub>2</sub> levels. Source: Gerhart and Ward (2010).

Over the past 60+ years there have been tens of thousands of studies on the response of plants to rising CO<sub>2</sub> levels. The overwhelming theme is that plants, especially C3 plants, benefit from extra CO<sub>2</sub>. There are two mechanisms by which CO<sub>2</sub> confers a growth benefit:

- Enhanced photosynthesis via the metabolic pathways described above.
- Increased water use efficiency. This arises because plants draw in CO<sub>2</sub> by opening the stomata (pores) on the leaf surface. When CO<sub>2</sub> is scarce the stomata must be kept wide open for long periods, which allows water to evaporate away. Under enriched CO<sub>2</sub> conditions the stomata are closed for longer periods helping the plant retain water longer, thereby increasing water use efficiency.

Specific effects of climate change on US agriculture will be reviewed in Chapter XX.

#### **Rising CO<sub>2</sub> and crop water use efficiency**

Deryng et al. (2016) surveyed evidence on crop water productivity (CWP), the yield per unit of water used, drawing attention to the potential for CO<sub>2</sub> both to enhance photosynthesis and reduce leaf-level transpiration (water loss during leaf respiration). They surveyed all available FACE data on crop yield changes for Maize (corn), Wheat, Rice and Soybean, and combined it with crop model data simulating yield responses as of 2080 under the extreme RCP8.5 scenario in four growing regions (Tropics, Arid, Temperate and Cold) each of which were split into rainfed and irrigated sub-regions. In every region they reported that models without CO<sub>2</sub> fertilization predicted CWP losses but CO<sub>2</sub> fertilization more than offset them so that all regions showed a net CWP gain. Deryng et al (2016) also reported that negative impacts of warming on wheat and soybean yields were fully offset by CWP gains and mitigated by up to 90% for rice and 60% for maize.

Similarly, Cheng et al. (2017) noted that increased global plant growth from 1982 to 2011 due to rising CO<sub>2</sub> uptake was accompanied by such large gains in CWP that despite the extra biomass global water use by plants had not increased.

Deryng et al. (2016) assumed that climate change would “exacerbate water scarcity”. It is noteworthy that while models predict drylands will expand under climate warming, current data show the opposite: greening is happening even in arid areas. Zhang et al. (2014) report that due to increased CO<sub>2</sub> levels “increasing aridity in drylands won’t lead to a general loss of vegetation productivity”; increased desertification will happen in at most 4% of currently arid areas.

### **Concealment of CO<sub>2</sub> fertilization benefits in IPCC Reports**

If CO<sub>2</sub> emissions had been discovered to be causing global crop declines and regional browning, that surely would have been discussed prominently in IPCC reports, perhaps even with its own chapter in an Assessment Report if not an IPCC Special Report on its own. By contrast the IPCC has been almost silent on the topic of global greening.

The topic is briefly acknowledged in a few places in the body of the IPCC 6<sup>th</sup> and earlier Assessment Reports but is omitted in all Summary documents. Section 2.3.4.3.3 of the AR6 Working Group I report entitled “global greening and browning” points out that the IPCC Special Report on Climate Change and Land had concluded with high confidence that greening had increased globally over the past 2-3 decades. It then discusses that there are variations in the greening trend among data sets, concluding that while they have *high confidence* greening has occurred, they have *low confidence* in the magnitude of the trend. There are also brief mentions of CO<sub>2</sub> fertilization effects and improvements in water use efficiency in a few other chapters in the AR6 Working Groups I and II Reports.

Overall, however, the Policymaker Summaries, Technical Summaries and Synthesis Reports conspicuously fail to discuss the topic.

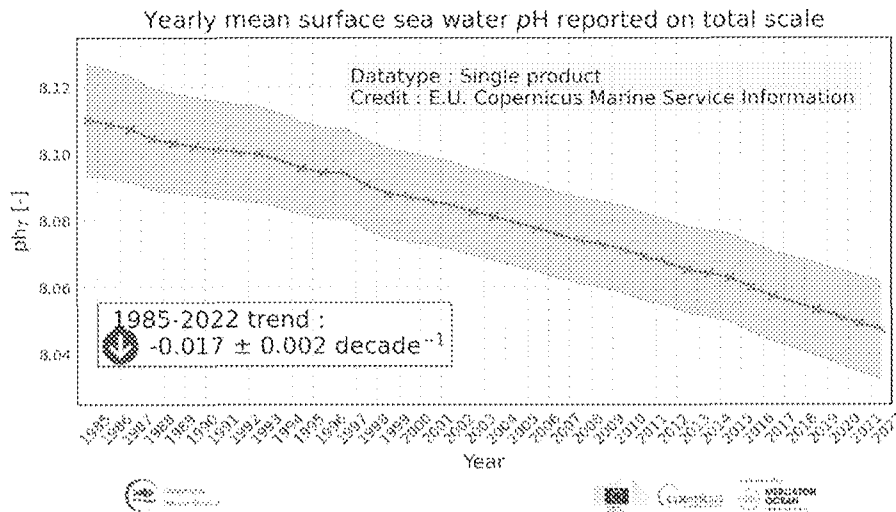
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### 3. Increasing CO<sub>2</sub> and the Alkaline Oceans

The modern-day global average pH of sea water is estimated to be 8.1, down from an estimated value of 8.2 in pre-Industrial times (Gattuso and Hansson, 2011).<sup>1</sup> As CO<sub>2</sub> concentrations in the atmosphere increase, more is absorbed by the oceans. Depending upon the alkalinity (buffering capacity) of the oceans, the oceans are expected to become somewhat less alkaline over time, putatively explaining the decrease in pH from 8.2 to 8.1 over the last few hundred years.



While this process is often called “ocean acidification”, it is a misnomer because the oceans are not expected to become acidic; “ocean neutralization” would be more accurate. And even if the water were to turn acidic, it is believed that life in the oceans evolved when the oceans were mildly acidic with pH 6.5 - to 7.0 (Krissansen-Totton et al., 2018).

It had long been assumed that a decreasing pH of sea water would reduce the calcification rate of coral reefs. But coral reefs already endure large swings in pH, partly due to daily photosynthetic activity in the reef; measured pH values range from 9.4 during the day to 7.5 at night (Revelle and Fairbridge, 1957).

In 2009 it was reported that a portion of Australia’s Great Barrier Reef (GBR, the world’s largest coral reef ecosystem) had experienced a 14% decline in calcification since 1990 (De’ath et al., 2009). This was tentatively attributed to increasing water temperature and decreasing pH. But that report was shown to have resulted from a biased data analysis (Ridd et al., 2013) which, when corrected, showed no change in calcification rates. Nevertheless, the alarm produced by the original paper has persisted as evidenced by the large number of published citations (541) received by the original study as compared to only 11 citations for the subsequent study (as of 30 April 2025).

Given the reported declines in GBR calcification between 1990 and 2009, it has come as a surprise that the decline reversed over the last decade or so, with Woods Hole Oceanographic Institution asking, “*Is the Great Barrier Reef Making a Comeback?*” (Woods Hole, 2023). The most recent annual summary of GBR conditions from the Australian Institute of Marine Science was titled, *Continued Coral Recovery*

<sup>1</sup> A neutral aqueous solution has a pH of 7.0, while one with pH > 7.0 is basic and pH < 7 is acidic.

*Leads to 36-year Highs across Two-Thirds of the Great Barrier Reef* (AIMS, 2022). Much of the decline in the GBR before 2011 turned out to be due to intense tropical cyclone activity (Beeden et al., 2015), and recovery of the reef from storm damage takes years.

On the time scale of thousands of years, boron isotope proxy measurements of pH show that ocean pH was around 7.4 or 7.5 during the last glaciation (up to about 20,000 years ago) increasing to present-day values as the world warmed during deglaciation (Rae et al., 2018). Thus, there appears to be considerable resilience of ocean biota to natural long-term changes in ocean pH since marine organisms are exposed to wide ranges in pH anyway.

It is being increasingly recognized that publication bias (alarming ocean acidification results preferred by high-impact research publications) exaggerates the impacts of declining ocean pH. An ICES Journal of Marine Science Special Issue addressed this problem with an article entitled, *Towards a Broader Perspective on Ocean Acidification Research*. In the Introduction to that Special Issue, H. I. Browman stated, "As is true across all of science, studies that report no effect of ocean acidification are typically more difficult to publish." (Browman, 2016)

Similarly, a meta-analysis of the negative effects of ocean acidification on reef fishes found that initially dramatic conclusions published in the scientific literature were all but refuted upon subsequent analysis involving larger sample sizes of data (Clements et al., 2021).

In conclusion, it is becoming increasingly apparent that the effect of ocean "acidification" on marine biota has been exaggerated.

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Woods Hole Oceanographic Institution (2023). Is the Great Barrier Reef Making a Comeback? <https://www.whoi.edu/oceanus/feature/is-the-great-barrier-reef-making-a-comeback/>

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**From:** Judith Curry <curry.judith@gmail.com>  
**Sent:** Friday, May 9, 2025 2:45 PM  
**To:** Steven Koonin  
**Cc:** Roy Spencer; John Christy; Ross McKittrick; Travis Fisher  
**Subject:** Re: attribution chapter  
**Attachments:** 7 Attribution.[RM].May08.docx

New attribution chapter is attached (ross sent this yesterday)

On Fri, May 9, 2025 at 11:34 AM Steven Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)> wrote:

Judy – your email text says “attribution chapter” but you attached chapter 5 (climate sensitivity). Can you straighten out the confusion?

SEK

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**From:** Judith Curry <[curry.judith@gmail.com](mailto:curry.judith@gmail.com)>  
**Sent:** Friday, May 9, 2025 12:27 PM  
**To:** Roy Spencer <[roywspencer@hotmail.com](mailto:roywspencer@hotmail.com)>; John Christy <[climateman60@gmail.com](mailto:climateman60@gmail.com)>; Steve Koonin <[steven.koonin@gmail.com](mailto:steven.koonin@gmail.com)>; Ross McKittrick <[ross.mckittrick@gmail.com](mailto:ross.mckittrick@gmail.com)>; Travis Fisher <[travis.scott.fisher@gmail.com](mailto:travis.scott.fisher@gmail.com)>  
**Subject:** attribution chapter

Latest version of attribution chapter is attached, Ross and I have hashed through this pretty thoroughly, we look forward to your comments

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## 7 Uncertainties in Climate Change Attribution

### 7.1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) distinguishes between detection of climate change and attribution of cause. As defined by the IPCC AR6 WGI Glossary (IPCC, 2025):

*Detection:* “Detection of change is defined as the process of demonstrating that climate or a system affected by climate has changed in some defined statistical sense, without providing a reason for that change. An identified change is detected in observations if its likelihood of occurrence by chance due to internal variability alone is determined to be small, for example, <10%.”

*Attribution:* “Attribution is defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with a formal assessment of confidence.”

Both steps rely on statistical analysis. Detection focuses on whether changes are significant enough to stand out from random variation regardless of cause. Attribution involves comparison of observed events to model-generated counterfactuals. Since experimentation on the climate is not possible attribution requires statistical inference to assess how much human activities, such as GHG emissions, versus natural factors, like volcanic eruptions, explain observed changes. Attribution methods assume all external and internal drivers of the system are known and represented.

There are ongoing scientific debates around attribution methods, especially for attributing extreme weather events to climate change. The IPCC has long cautioned that methods to establish causality in climate science are inherently uncertain and ultimately depend on expert judgement. The Fourth Assessment Report: The Physical Science Basis (Hegerl et al., 2007) explained it as follows:

‘Attribution’ of causes of climate change is the process of establishing the most likely causes for the detected change with some defined level of confidence... unequivocal attribution would require controlled experimentation with the climate system. Since that is not possible, in practice attribution of anthropogenic climate change is understood to mean demonstration that a detected change is ‘consistent with the estimated responses to the given combination of anthropogenic and natural forcing’ and ‘not consistent with alternative, physically plausible explanations of recent climate change that exclude important elements of the given combination of forcings’ (IPCC, 2001)... The approaches used in detection and attribution research described above cannot fully account for all uncertainties, and thus ultimately expert judgement is required to give a calibrated assessment of whether a specific cause is responsible for a given climate change.

The Fifth Assessment Report Working Group II makes the following statement: (Cramer et al., 2014):

“Two broad challenges to the detection and attribution of climate change impacts relate to observations and process understanding. On the observational side, high-quality, long-

term data relating to natural and human systems and the multiple factors affecting them are rare. In addition, the detection and attribution of climate change impacts requires an understanding of the processes by which climate change, in conjunction with other factors, may affect the system in question.”

Because of the complexity of the causal chains in the climate system, investigation of these relationships is exceptionally challenging.

## 7.2 Attribution methods

The Intergovernmental Panel on Climate Change (IPCC) employs several attribution methods to assess the causes of observed climate changes, distinguishing between natural and human-induced factors. Below is a concise description of the key methods that have been used by the IPCC:

*Optimal Fingerprinting* uses linear regression to explain variations in observed climate data as a weighted sum of climate model simulations run with and without anthropogenic forcings. The data used in the regression model are weighted to try to minimize the influence of random noise and the estimation method is chosen to take account of climate model error.

*Time Series Analysis* exploits statistical differences between anthropogenic forcing and natural variability to see which one dominates observed temperatures, and also uses variations in the timing of changes to determine if causal dependence across data series can be inferred.

*Process-Based Attribution* focuses on understanding the physical mechanisms behind observed changes. This approach combines observations, climate models, and theoretical understanding to attribute changes in specific processes to forcings. This approach is often used for regional climate phenomena, such as monsoon changes or polar amplification

*Extreme Event Attribution* assesses in the role of human influence in the likelihood of occurrence or intensity of extreme weather events (e.g. heat waves, droughts). Methods include:

- Probabilistic Event Attribution uses large ensembles of climate model simulations to compare observed events to model-generated counterfactuals
- Storyline Approach examines the physical processes driving an event and evaluates how anthropogenic forcings may have modified those processes

## 7.3 Attribution of global warming

Attribution statements for global warming in the three most recent IPCC Assessment reports are:

AR4: “Most of the observed increase in global average temperatures since the mid-20<sup>th</sup> century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations.” (IPCC, 2007)